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Relationships Between Physical Textile Properties and Human Comfort During Wear Trials of Chemical Biological Protective Garment Systems

by

Catherine Jane Andersson ©

A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

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in
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This thesis is dedicated to
my mom.

ABSTRACT

A two phase design was used to investigate the ability of textile properties to predict the comfort of chemical/biological (CB) protective clothing. In phase I differences in various forms of *dry and evaporative heat transfer*, *moisture vapour transfer*, *moisture absorption* and *air permeability* among CB fabric systems were determined.

In phase II, data from wear trials of CB garments, comprising physiological and subjective comfort measures were supplied by the Department of National Defence. Pearson's correlations determined relationships between textile properties and wear trial measures. Multiple linear regressions were used to determine which textile properties would best predict human responses.

Differences in physiological and subjective measures reflected differences in textile properties. Regression models indicate that different physical textile properties determine different physiological measures, but the same physical properties determine corresponding subjective comfort measures. Regression models suggest that it is necessary to measure only one or two textile properties to predict comfort.

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Chapter 1

INTRODUCTION

The clothing that one wears on a daily basis will provide some degree of physical protection, however, there are specific work place hazards that require a greater level of defence through the use of protective clothing. Wearing comfortable protective clothing will contribute to increased worker morale and productivity (Barker and Scruggs, 1996). However, protection is often achieved at the expense of workers' comfort. It is thought that comfort and protection offered by clothing are two contradictory properties (Zimmerli, 1996). In order to provide adequate protection from work and environmental hazards, clothing must have a very low permeability to chemical substances, mechanical impact, heat and other hazards. On the other hand, clothing comfort is achieved in part by the movement of evaporated sweat away from the body through permeable clothing.

Protection provided by clothing against work place hazards can be grouped into five categories: chemical, thermal, mechanical, nuclear and biological (Raheel, 1994). For this study discussion will focus on the chemical/biological (CB) hazards encountered by Canadian Forces (CF) personnel. CB protective clothing is worn by CF personnel during military training exercises and in times of war when there are threats of chemical or biological attack. When worn properly, CB protective suits are designed to prevent damage to the body and fatalities from the effects of CB agents.

Chemical and biological substances may reach and harm the body by four different routes. The first is by direct contact with the skin and dermal absorption. The second is by breathing in any hazardous substances. When inhaled, disease bearing micro-organisms may destroy the lining of the lungs or move through the lungs to affect blood or nervous systems. The third method of becoming infected is by ingestion of CB agents directly or indirectly through contaminated food or drugs. The fourth possible source of exposure is by direct injection of CB substances into the body (Watkins, 1995).

CB protective clothing and equipment worn by CF personnel is designed to protect the wearer against the first two threats. CB protective clothing along with masks, respirators and gloves will prevent CB hazards from touching the skin or from being inhaled. Adequate protection from CB agents is accomplished by using a garment assembly that will withstand a large range of hazards, maintain its integrity during wear and decontamination processes and provide an acceptable level of comfort to the wearer.

CB Protective Clothing

Although chemical and biological hazards involve different substances, the clothing systems used to protect the body from both hazards are similar. For this reason many clothing ensembles are designated as providing both chemical and biological protection (Watkins, 1995). Some believe that the answer to protecting against CB agents is to have a totally impermeable garment that is impenetrable by any toxic substance. However, the issue of human comfort would dictate the likelihood of workers adopting this type of protective assembly.

There are no inherently CB resistant fibres. Therefore, textile materials are made CB resistant by using treated fabrics and films or by incorporating into the textile, components that will absorb CB substances. A CB protective suit can be worn instead of, or combined with regular battle dress. The outer layer generally consists of an oil/water resistant textile material and the inner layer of a finely ground activated carbon that is attached to a plastic or foam material; carbon fibres may also be used (Gripstad, 1983). A foam impregnated with carbon is the main protective component used in the CB protective suits currently worn by CF personnel. By using a protective carbon layer a perm-selective barrier can be achieved that allows the diffusion of water vapour and air, but limits the diffusion of CB agents (Watkins, 1995). Activated carbon used in the protective layer has many attractive sites that will absorb hazardous molecules. Due to the fact that carbon will absorb CB agents as well as moisture it is important to control the amount of water vapour and liquid perspiration within the protective assembly. This is critical when CB clothing is worn in hot environments or when workers wearing the clothing are perspiring heavily, as effectiveness of the protective carbon layer will be reduced when excess moisture is absorbed.

Human Body and Comfort

The topic of comfort in protective clothing has been of interest to researchers for many years. When considering comfort of protective clothing, thermal comfort and fit are important factors to investigate. The fit of a protective garment is critical as it must not impede the mobility of the wearer. Thermal comfort, the property of interest in this study, is achieved by maintaining the balance of heat exchange between the body and the environment. More specifically, when thermal balance is achieved, an equal amount of energy is produced and lost by the body. Failure to maintain this thermal balance within the body will lead to reduced work efficiency and health risks. It is essential to maintain a constant core temperature under different environmental conditions as well as different work levels (Keighley, 1985).

The methods employed by the human regulatory system to maintain thermal balance are highly effective. The mechanisms of interest for this study are those utilised to increase the heat transfer from the body. When the body is warm, blood flow to the skin is increased to a maximum, temperatures of the arms and legs are raised to almost core body temperature and evaporative cooling starts (Mecheels and Umbach, 1977). The evaporation of sweat from the skin is the most effective temperature regulating mechanism of the body.

The evaporation of perspiration removes heat from the body and contributes to the body's overall heat balance. The body is constantly producing perspiration that evaporates within the skin layers and is emitted in the form of water vapour called insensible perspiration. Sensible perspiration is the liquid sweat that appears when the ambient temperature is high or an individual is doing physical work. Interest in the passage of moisture through textile materials is due to the fact that the body is continuously losing moisture mostly in the vapour form (Parsons, 1994; Fourt and Hollies, 1970). Clothing worn by an individual will moderate the exchange of energy and moisture between the body and the environment. The loss of moisture through clothing is very important for maintaining heat balance and comfort. If protective clothing does not allow the exchange of heat and moisture it will lead to a feeling of discomfort. As a result, workers will make excuses for not wearing protective clothing that is uncomfortable or maladapted to the wearer.

Statement of the Problem

Movement of heat and moisture through textile materials plays an important role in determining the level of comfort provided by a clothing system. Ideally, the function of chemical/biological protective clothing is to protect the body against injury and external hazards, while at the same time maintaining a high degree of comfort. Materials in a CB protective assembly must be selected to reduce the accumulation of perspiration and excess heat. The presence of liquid sweat and surplus heat will cause a sensation of discomfort and will reduce the work efficiency of personnel wearing protective garments. The build up of moisture inside a garment can also lead to serious physiological overloading, and even death if the situation is not altered (Slater, 1996). Due to the problems associated with the accumulation of energy and perspiration in a protective clothing system, the Department of Human Ecology at the University of Alberta has embarked on a project with the Department of National Defence to study the phenomena of moisture and heat transfer through textile materials, used in CB defence suits.

The purpose of this research is to investigate the physical textile properties that will affect the comfort of protective clothing. The main focus of the study is to examine various modes of heat and moisture transfer and air permeability through CB protective textile materials. From data obtained from the small scale tests, indices will be developed to correlate physical laboratory data with subjective and physiological comfort measures from human wear trials of different CB protective clothing ensembles.

Justification

A large amount of research has been conducted on the subject of human comfort by researchers worldwide, but there is little agreement on appropriate measures to assess comfort or to evaluate the capability of protective clothing to provide comfort. This work will contribute to a better understanding of specific phenomena involved with comfort of protective clothing systems. The fabric systems tested are specifically intended for CB protection. Dry heat loss, evaporative heat loss, air permeability, absorbency and two types of water vapour diffusion tests are considered critical measures when correlating the textile data to human comfort and developing comfort indices based on physical textile properties.

This study is part of a larger program on protective clothing, and more specifically, part of a contract effort for Defence Research Establishment Suffield. The practical and theoretical goal of this research will be an increased understanding of comfort properties of protective clothing as measured through physical laboratory testing. This research project was designed to contribute to improved techniques for the measurement of comfort related textile properties, as well as the development of performance and testing standards for protective clothing.

Objectives

The objectives of this study were the following:

1. To measure various forms of *dry and evaporative heat transfer*, *moisture transfer* and *air permeability* through textile materials commonly used in chemical/ biological defence suits, and to determine differences in these measures among fabric systems.

2. To determine differences in comfort related measures between garment systems when worn:
   a) differences in physiological measures between garment systems 3 and 4,
   b) differences in physiological measures between garment systems 2 and 3,
   c) differences in subjective comfort measures between garment systems 3 and 4,
   d) differences in subjective comfort measures between garment systems 1 and 2.

3. To determine relationships between various indices of *dry heat transfer, evaporative heat transfer, moisture vapour transfer, moisture absorption, and air permeability* of textile materials and measurements taken during human wear trials of clothing constructed of those CB materials:
   a) relationships with physiological measures, and
   b) relationships with subjective comfort measures.

Statement of Null Hypotheses

To meet objectives 1, 2 and 3 the following null hypotheses will be tested:

Ho_1: There are no significant differences in physical textile properties among the CB protective fabric systems.

Ho_2: There are no significant differences in physiological measures from human wear trials between CB protective garment systems 3 and 4 at each exercise level.

Ho_3: There are no significant differences in physiological measures from human wear trials between CB protective garment systems 2 and 3.

Ho_4: There are no significant differences in subjective comfort measures from human wear trials between CB protective garment systems 3 and 4 for each level of physical effort.

Ho_5: There are no significant differences in subjective comfort measures from human wear trials between CB protective garment systems 1 and 2.

Ho_6: There are no relationships between physical textile property measures and human physiological measures for garment systems 3 and 4.

Ho_7: There are no relationships between physical textile property measures and human physiological measures for garment systems 2 and 3.

Ho_8: There are no relationships between physical textile property measures and human subjective comfort measures for garment systems 3 and 4.

Ho_9: There are no relationships between physical textile property measures and human subjective comfort measures for garment systems 1 and 2.

Delimitations and Limitations of the Study

A delimitation of this research is that the fabric systems are chemical/biological protective fabrics supplied by the Department of National Defence. A limitation that will affect this study is that the human wear trial data is secondary. Therefore the data available will be restricted to what is accessible from the completed trials. As the researcher did not have input into the planning of the human wear trials, some questions may not be answered based on the specific subjective and physiological measures taken during the trials.

Definitions

For the purpose of this research the applicable terms are defined as follows:

Air permeability: "The rate of air flow passing perpendicularly through a known area under a prescribed pressure differential between the two surfaces of a material." (ASTM, 1996, p. 236)

Clo: The primary unit used when discussing thermal insulation of a clothing ensemble is the Clo unit; the total thermal insulation of a clothing system can be added up layer by layer. In physical terms, one Clo unit is equivalent to a thermal resistance of 0.155°C m^2 /W (Fourt and Hollies, 1970) which is thought to be the average thermal insulation of a business suit, and the thermal insulation required to keep a sedentary person comfortable at 21°C (Parsons, 1994).

Comfort: "Human comfort is conceived as a mental state of ease or well-being, a state of balance or equilibrium that exists between a person and the environment." (Sontag, 1985,

p. 10). "One of the prerequisites for good wear comfort is that a garment's thermal and moisture transport properties are adapted to the specific climatic and activity conditions in such a way that the heat and moisture exchange between body and surrounding atmosphere are balanced." (Umbach, 1988, p. 139)

Heat strain: Occurs when the body cannot dissipate excess heat. The temperature and humidity may be too high, the body may be gaining heat from the environment, or the protective clothing worn may be preventing sweat evaporation which provides necessary cooling required by the body (Goldman, 1988).

Heat transfer: "Heat energy is the energy which is transferred from a warm body to a cooler one as a result of the temperature difference between the two bodies." (Bueche, 1980, p.289). In the heat transfer process, heat is transferred from its source or between two substances by three different processes (radiation, conduction, and convection). If there is no difference in temperature within a body or between two substances, no net heat flow will occur.

Heat transfer as it relates to textile materials is the ability of a fabric to allow the flow of heat energy by one or a combination of the following mechanisms: conduction, convection, radiation, and/or evaporation.

Conduction: Occurs when two objects are in contact with each other. Heat will flow from the warmer object to the cooler one (Watkins, 1995).

Convection: Involves the transfer of heat energy by actual motion of either a gas or a liquid. When liquids and gases mix, a heat exchange will occur as the warm and cold particles integrate (Harris and Hemmerling, 1972).

Radiation: Radiative heat is transferred by electromagnetic waves. This process does not require liquids or gas, or contact with matter. The transfer of heat by radiation involves the transmittance of radiant energy (not heat) by electromagnetic waves. These electromagnetic waves are then transformed into heat once they hit an object (Watkins, 1995).

Evaporation: An important process for the heat exchange of the human body. During this process heat is transferred when a liquid changes into a gas. For example, this mechanism will occur when perspiration is evaporated from the skin's surface. The vaporization will use heat produced by the body to evaporate the liquid sweat, thus dissipating heat (Watkins, 1995).

Index: A model developed to compute the interaction of several factors and its effect on a dependent variable (Holmer, 1995). An index will give a single number expression which integrates the various contributing factors.

Moisture transfer:
Water Vapour Transfer: Water vapour transfer as it relates to a fibrous material is the ability of the textile to transport moisture through it in vapour form (Slater, 1986).

Absorbency (wicking and wetting): Absorbency is the transportation of liquid in a textile by the combined phenomena of wicking and wetting. The movement of liquid perpendicular to the plane of the fabric is called transplanar flow or demand wettability. Planar flow is defined as the movement of liquid in a parallel direction to the plane of the fabric, also known as wicking (Hussain and Tremblay-Lutter, 1996). Wicking is thought to be one of the factors that will affect the comfort of clothing worn in hot climates or during high activity levels. A fabric that wicks well will promote quick drying and thus faster cooling of the body.

Protective clothing: A piece of clothing designed and worn to protect from one or more hazards likely to threaten a worker's health or safety. Protective clothing does not affect ambient hazards or eliminate dangerous actions. Protective clothing will modify the energy exchange that occurs during an accident, minimize the consequences of accidents and the likelihood of contracting an occupational disease, and reduce the severity of injuries (Menard, Savoie and Thibeault, 1991).

Thermal comfort: "Thermal comfort is defined as that condition of mind which expresses satisfaction with the thermal environment."(ISO 7730, 1994 (E), p.5) Therefore, there are no common set of environmental or body temperatures that will satisfy everyone.

Chapter 2

REVIEW OF LITERATURE

With advances in textile technology, and an increasing need for high performance protective wear, requirements for fabrics and clothing include not only protection and durability, but also comfort. In the following review, comfort as it relates to protective clothing will be discussed. Explanations of the concept of comfort, a review of research in the area of measuring textile properties related to clothing comfort and the prediction of comfort based on models and indices will be included.

Meaning of Comfort

Many scientists have asserted that comfort, as it relates to clothing, defies definition. Slater (1986) stated that it is impossible to give a quantitative definition of comfort since it is a subjective feeling. However, other researchers have attempted to describe the ambiguous term comfort. Sontag (1985) gives a general definition of comfort as a mental state of well-being, or a state of equilibrium that exists between a person and the environment. Smith (1993) views comfort as a neutral sensation, a freedom from pain, and ultimately, the wearer being unaware of the clothing that is worn. Thus, discomfort would describe a situation in which the wearer is conscious of the clothing worn, and that the experience is unpleasant. Feelings of discomfort can range from a minor feeling of irritation to extreme pain. Ultimately, comfort is a universal need, that all humans constantly try to maintain and improve (Slater, 1986).

Comfort is a broad concept that can be divided into smaller components. Shivers, 1980, defines comfort in physiological and psychological terms. Physiological comfort refers to maintaining thermal balance by counterbalancing the relationship of body heat production and loss. Umbach (1988) claims that comfort is not an individually different and undefined varying sensation, but is directly caused by particular physiological quantities of the body. Psychological comfort is explained in terms of individuals needing certain clothing to help make them feel confident and at ease within the context of various situations. These two categories will influence each other and produce an overall comfort sensation. For the purpose of this report, the review of literature will focus on the physical textile properties of fabric systems that will affect physiological comfort.

Textile Properties and Physiological Comfort

The level of comfort provided by a fabric is difficult to measure, however, there are specific physical textile properties that may be measured in an attempt to predict how well a fabric will perform. When assessing comfort, a wide range of these interrelated properties must be considered. Basically a textile material should be evaluated in terms of the most general functional properties: thickness, weight, thermal insulation, resistance to evaporation, and air penetration (Fourt and Hollies, 1970). Three clothing factors relate directly to thermal comfort. First is the overall thickness of the materials and air spaces between the skin and the environment. Second is the extent to which air can penetrate the clothing by wind or wearer motion. Finally, fabric should not restrict evaporation of perspiration.

Many researchers agree that a major factor contributing to comfort is the movement of heat and moisture through a garment system (Cheng & Cheung, 1994; Gibson, 1993; Hatch, Woo, Barker, Radhakrishnaiah, Markee, & Maibach, 1990; Slater, 1977). Evaporation of moisture and the dissipation of heat from a clothed body depends on the following factors: the wearer's activity level, humidity in the environment, external air movement, fabric thickness, enclosed air spaces, fabric structure and fibre content (Slater, 1986; Cheng & Cheung 1994; Meinander, 1988). Ideally, clothing should buffer against environmental changes, and move moisture away from the body without feeling wet. When a fabric has a high moisture resistance, perspiration and heat cannot be dissipated resulting in a feeling of discomfort (Guanxiong, Yuan, Zhongwei, Jianli, Min, & Jie, 1991). Clothing that has a high water vapour permeability will allow the body to maintain a comfortable state by evaporation of perspiration (Gibson, 1993).

Thermal transmittance is another critical factor of comfort. The body can gain heat from the sun and other radiant bodies, by internal metabolism, or by exercise; heat loss can occur by conduction, convection, radiation, or evaporation (Slater, 1977). The presence of moisture in a clothing system will have a significant effect on heat transfer between the body and the environment (Parsons 1994). "It is important to realize that the clothing is not just a passive cover for the skin, but that it interacts with and modifies the heat regulating function of the skin and has effects which are modified by body movement."(Fourt and Hollies, 1970, p. 31). The transfer of heat and moisture through a textile material is a complex process that is affected by several interrelated factors. For this reason, movement of heat, moisture and air through a garment assembly is of great importance in the assessment of comfort.

Assessment of Comfort

Comfort may be studied using a number of theories and test methods. These methods include subjective and objective testing. Physiological testing can only be carried out on live humans. The measures obtained from these tests include measures of body response mechanisms that are not subjective. Subjective measures must also be taken from humans, as no laboratory test equipment has been developed that can predict how comfortable a person will feel while wearing different garments. Objective testing includes human physiological measures and laboratory tests involving equipment designed to measure certain textile properties while simulating to some degree actual conditions of wear.

For a number of reasons, some researchers believe that results obtained from subjective human wear studies may not be reliable. Slater (1986) remarked that subjects may not tell the truth, resulting in the problem of inconsistent responses. In addition, what the subject is feeling may be something totally unrelated to what is being studied. Since the time of his 1986 publication, however, Slater (1996) along with others (Smith, 1993 and Parsons 1994) now believe that human wear trials are the only valid method to assess clothing comfort. Parsons points out that although human wear trials of clothing are expensive they do provide realism. Parsons also notes that humans differ too much from mannequins to be able to compare results from both measures. Testing humans may reduce the level of control in testing, however, the results may be more valid and will be representative of how a human really perceives a garment in practical situations.

Another method to predict the comfort provided by clothing is to study the physical textile properties such as various forms of moisture, heat and air transfer that are related to human comfort sensations. Small scale laboratory tests are a practical alternative to expensive, time consuming wear trials (Smith, 1993; Slater, 1986). Laboratory measures of heat and moisture vapour transfer of textiles are convenient for comparing different fabrics, however, they do not take into account factors that are also related to garment fit and design (Gibson, 1993). Predictions of comfort are often erroneously made from the results of laboratory tests. Data from physical laboratory test results are limited in use to making comparisons among fabrics. Results from one small scale test do not lend themselves to broad generalizations or predictions of actual perceived comfort sensations.

Laboratory tests usually measure one or two textile properties under controlled conditions. Once a textile is made up into a garment there are several factors that will affect the wearer's perceived comfort. The advantage of human wear trials is that they will take into account complex combination of environmental conditions and garment design. The only way to be assured that predictions from small scale tests are reliable is to compare the results with human wear trials. Therefore, it is often necessary to apply a holistic approach when studying the effects of clothing on the human body. For this reason, physiological measurements and perceived comfort ratings from human wear trials are often correlated with laboratory tests.

In recent years, several new effective and accurate test methods have been developed to measure heat and moisture transfer objectively. For the purpose of this research, objective methods to measure the various forms of heat and moisture transfer and air permeability will be investigated.

Measuring Heat and Moisture Transfer

As heat and moisture transfer through fabrics are thought to be the most important factors affecting clothing thermal comfort there have been numerous studies carried out to examine how heat and moisture pass through a clothing system. Hatch et al. (1990) describe four critical factors in determining the degree to which a fabric dissipates heat from the body in a hot humid environment. These include the ability of the fabric to allow air movement, heat flow, passage of water vapour and transport of liquid water. A summary of previous research on different test methods developed to measure heat and moisture vapour transfer, and a summary of research comparing results from wear trials with objective laboratory small scale test measures will help explain these variables.

The review of literature will first focus on a discussion of the movement of moisture through clothing in vapour form. Then a following section will address movement of moisture in liquid form. Information from the cited research focuses on the specific test methods, not the fabrics being tested. Therefore, actual results from research studies will not be reported or discussed as these are not the primary focus of this review.

Measuring Heat and Moisture Vapour Transfer Separately

Water Vapour Transfer

Water may evaporate on the skin surface and pass through a fabric in vapour form, allowing the pores of the fabric to remain free of liquid. This enables air to move through the fabric and allows heat insulation of the fabric to be maintained (Slater, 1977). The rate at which water vapour will pass through a fabric depends on the microporous nature of the material. A traditional technique for determining water vapour transmission through a fabric is known as the *control dish* or *upright cup method*. Six dishes are placed on a turntable with a measured amount of water in each container. The test fabric is secured over three of the dishes. Therefore, any water that evaporates from the dishes must pass through the fabric. The change in the mass of water from each container as a function of time is determined. The transmission rates of the dishes with and without test samples provide a measure of moisture vapour resistance (Slater, 1986). This was a Canadian standard method until a less time consuming and simpler test replaced the control dish method in 1991.

Most of the initial work done in the area of moisture vapour diffusion of textile materials was carried out during the second World War. The main focus was to evaluate the suitability of tightly woven fabrics for jungle clothing. Fourt and Harris (1947) used two methods to calculate the diffusion rate of fabrics: the *absorption cup method* and the *evaporative procedure*. The evaporative procedure is similar to the traditional upright cup method. The absorption cup method differs in that the fabric is sealed to a small dish containing a granular drying agent. The dish is then inverted, and the drying agent is in contact with the fabric. The rate of gain in weight of the test unit is then measured at uniform intervals of time.

Over the years, attempts have been made to improve on traditional methods for water vapour transmission. Watkins and Slater (1981) compare the upright cup method for water vapour transmission to a relative humidity gradient tube (R Tube) technique. The R tube consists of a polyvinyl chloride tube, 40 cm in length and 2.54 cm in diameter. At one end of the tube is a cell which holds distilled water that acts as a source of water vapour. The other end is a cell filled with a water absorbing substance. In the centre is the specimen holder with four relative humidity sensors mounted two on each side of the fabric holder. Analysis of the results obtained from both test methods indicated that the results were equivalent. The results from the R Tube required a maximum of three hours where as the "standard method" required a time of 17 to 18 hours for a determination of water vapour transmission. Despite the improvement in time required to test a fabric, the R Tube had a sensitivity of only half of the "standard method". The new method was thought, by the researchers, to be sensitive enough for practical use. However, the R Tube was never adopted as a standard method. Farnworth and Dolhan (1984) would later develop an apparatus to measure the water vapour resistance of textiles which would become the current Canadian standard method.

The problem with the R Tube's reliance on carefully calibrated sensors is eliminated in Farnworth and Dolhan's apparatus to measure the water vapour transmission of textiles (DND method). The technique is similar in speed to the R Tube, however, the apparatus is different. The specimen is sandwiched between two layers of microporous film. One layer of the film separates the specimen from a supply of dry air and the other forms the bottom of a water dish. The resistance of the total system is calculated from the loss of water from the dish. The resistance of the microporous films is established in a separate run without the specimen and is subtracted from the total system measurement to give a resistance rating in units of millimetres of still air.

Dolhan (1987) compared four different pieces of equipment used to measure water vapour resistance of textiles. She found that both the traditional CGSB control-dish method and the DND method described earlier produced results that were accurate. However, Dolhan states that the DND method is capable of reducing some of the error which is present in the control-dish method. The DND method does not require a conditioned atmosphere in which to conduct the testing. Furthermore, there is less time required for specimen preparation, and preliminary results may be obtained in an hour. The disadvantage of the DND method is that the occurrence of even small pin holes in the microporous film will give false results. In addition, due to the design of the equipment, there is also the problem of compressing thick samples. A new version of the CGSB test method No. 49 for Resistance of Materials to Water Vapour Diffusion is similar in design to the DND method. However, this method is able to overcome the problem of compressing thick samples by having different test options. Two of these options use spacers to create air layers between the specimen and the dish. The position of the specimen in relation to the dish will simulate a dry test condition (air layer between the fabric and the body) or a wet condition (no space between the fabric and the body).

Van Beest and Wittgen (1986) added to the body of knowledge by developing an apparatus to measure the water vapour resistance of textiles. The apparatus is simple to operate and compared to Farnworth and Dolhan's apparatus, measurements of water vapour resistance are made faster, within half an hour, and specimens are not compressed.

The fabric specimen is sandwiched between two microporous membranes. The upper membrane faces an air chamber and the bottom membrane faces a water chamber. A pipette is connected to the water chamber. The amount of vaporized water per unit of time is measured with the pipette and a stopwatch. This method of measurement is thought to be more accurate than the Farnworth and Dolhan method of measurement which uses the difference in weight of the whole apparatus which has a high resistance to water vapour. Van Beest and Wittgen believe that the construction of their apparatus is such that it is capable of increasing the reliability, overcoming the problem of specimen compression and producing rapid results.

Up to now all of the different measures of water vapour diffusion described have been equilibrium test methods. These types of tests are easy to use, but do not give information on dynamic properties of textile materials which are important under transient conditions typical of real life situations. The Dynamic Moisture Permeation Cell is a water vapour diffusion test developed by Gibson, Kendrick, Rivin, and Charmchi (1997) which allows for testing the behaviour of these textiles under nonstandard conditions on small quantities of fabrics. The apparatus consists of nitrogen streams containing a mixture of dry nitrogen and water-saturated nitrogen that are passed over the top and the bottom surfaces of the fabric specimen. The relative humidity of the streams is varied by controlling the proportion of the saturated and dry components. The water vapour diffusing through the test sample may be determined by measuring the temperature and water vapour concentration of the entering nitrogen flows, and by measuring the temperature and water vapour concentration of the nitrogen flows leaving the cell. This method allows for control over temperatures, pressures, and vapour concentrations which is not possible in most existing standard laboratory methods. Research findings suggest that water vapour permeation results with the Dynamic Moisture Permeation Cell are in excellent agreement with those from the ISO 11092 sweating guarded hot-plate test method, and correlate well with a modified ASTM E 96 inverted cup test.

Heat Transfer

Thermal transmission is thought to be one of the most important factors affecting clothing comfort (Satsumoto, Ishikawa and Takeuchi, 1997). The thermal insulation of clothing is affected by many physical factors such as: fabric thickness, the amount of body surface area covered by the garment, garment design (looseness and tightness) and number of fabric layers. "A textile structure is essentially a mixture of fibers, air, and moisture, each having distinctively different thermal properties, so the thermal behavior of the system is the collective and interactive results of these three constituents." (Jirsak, Gok, Ozipek, Pan, 1998, p. 47).

McCullough and Jones (1984), explain how clothing affects energy loss from the body in terms of the four mechanisms of heat transfer. In general, clothing blocks conductive heat loss by trapping air within the fabric and between garment layers. Clothing will resist convective loss by preventing convection currents from forming next to the body and by providing a barrier against air currents in the environment. Clothing will also reduce radiant heat loss as each layer serves as a thermal radiation barrier. Finally, clothing reduces evaporative heat loss by restricting the evaporation of sweat produced by the body.

Due to the complex interactions between the human body and clothing systems, some researchers have decided to exclude all body/clothing interactions and characterize thermal performance of the fabric alone (Bomberg, 1991). Bomberg believes that including the aspect of sweating into a laboratory test would only be useful if all the population perspired the same way as the test equipment. The objective of Bomberg's study was to modify the following existing ASTM methods in order to use these non-textile standards to measure thermal resistance of clothing materials: Guarded Hot Plate (ASTM C177), Heat Flow Meter (ASTM C518) and Thin Heater (ASTM C1114). Results from these three standard test measurements varied for a number of reasons. One of the reasons for the differences in results was an insufficient power supply in the Thin Heater apparatus. However, the main differences were probably a result of different patterns of heat flow. Although each standard test uses a different method, they all measure the same phenomenon of thermal resistance and were found to be acceptable for testing insulating clothing. In addition, these apparatuses can be used with textiles in the same manner as they would be used for testing industrial insulation materials.

Dry heat transfer was measured by Satsumoto, Ishikawa and Takeuchi (1997) using a vertical hot plate to simulate the human body. Their work tested whether or not a vertical hot plate could be used as a substitute for thermal mannequins which are now emerging as substitutes for the human body. The effects of clothing design factors on heat transfer were tested with experiments done on the abdominal section of the thermal mannequin and the vertical hot plate. A comparison of the results from both methods indicated agreement when the air layer was large (20 mm). When the size of the air layer was small (5 and 10 mm) the mannequin results were inconsistent with those of the hot plate. From their findings, the researchers concluded that when investigating the effect of textile physical properties on heat transfer it is not necessary to use a full scale mannequin. However, they do admit that testing with a mannequin can not be substituted when heat transfer is being measured on full garments and the effects of complex garment construction factors are being evaluated.

Measuring Heat and Moisture Transfer Simultaneously

Attempts to measure heat transfer when combined with the movement of moisture are of critical importance when considering the performance of protective clothing. Simultaneous testing of heat and moisture transfer is thought to more closely represent conditions of actual wear than non-simultaneous testing of these phenomena due to the interactions that occur between a human body and a clothing system. The phenomena of heat and moisture transfer do not occur separately in humans. The body is continuously giving off moisture in the form of vapour or liquid (insensible and sensible perspiration). In order to maintain a balance between self and the environment, heat is lost through evaporation of moisture. The amount of heat transferred by the human body is partly influenced by the amount of moisture (perspiration) produced. As a result, separate measures of heat and moisture transfer may not accurately depict real life situations.

The way a clothing assembly affects heat loss from a sweating body has been studied in detail using simulated sweating instruments. In previous research, test equipment was developed by Meinander (1988) to simulate a sweating skin surface that would measure both heat and moisture transmission through textiles under different environmental conditions. Meinander's Sweating Cylinder produces heat and moisture similar to that of the human body. The apparatus functions as follows: the cylinder wall is heated to skin temperature; water is supplied to the surface where it then evaporates. When a fabric is tested on the cylinder water vapour may only be partly transferred through the textile. The rest condenses on the inner fabric surface. The apparatus measures the energy required to maintain the surface temperature of 35 °C (a temperature corresponding to that of human skin). The amount of water condensing on the inner surface of the specimen is determined by weighing the specimens before and after the test.

In addition to the Sweating Cylinder tests, Meinander performed corresponding tests for Thermal Insulation (BS 4745:1971) and Water Vapour Transmission (Upright Cup or Dish method ASTM E96-66). Although the Sweating Cylinder gave lower results than the thermal insulation tests, there was a good correlation between both tests for thermal resistance. On the other hand, the ratings from the water vapour transmission test did not correlate with the results of the Sweating Cylinder.

Given the lack of consistent correlation between the three test methods performed by Meinander, it remains uncertain whether the Sweating Cylinder is the most appropriate test method. It is also debatable whether predictions of comfort can be made accurately from these results alone. The author has suggested that a movable, sweating, thermal mannequin be used to examine the effects of the complete garment assembly, including size, fit and ventilation on moisture and heat transfer.

One of Gibson's (1993) research goals was to evaluate the moisture vapour permeability of a textile by comparing two different test methods: the Sweating Guarded Hot Plate and the Upright Cup method. The results from the two test methods indicated that there was a correlation for permeable materials. However, semi-permeable membranes showed poor agreement between the two tests. In this case the Sweating Guarded Hot Plate may be regarded as the superior test method as the apparatus more closely simulates the heat and moisture transfer of the human body. In the third part of

Gibson's study, heat transfer and water vapour permeability results were compared at three different laboratories. Each facility had a guarded sweating hot plate to determine the dry thermal resistance and water vapour permeability of textiles. The goal was to observe how differences in laboratory practise would affect the results from each laboratory. The differences included: plate and air temperatures, ambient humidity and air velocity flowing over the apparatus. Gibson found that the results obtained from the three different kinds of sweating hot plates compared well as long as the differences in air flow were taken into account.

In recent years, there have been several new methods developed for measuring heat and moisture transfer. By simulating clothing and body conditions, and matching air spaces, Kim and Spivak (1994) were able to detect changes in moisture vapour and temperature by air sampling using microhygrometry and miniature thermometers. The test apparatus used in this study measures the microclimate temperature and vapour pressure close to the fabric surface while mounted over a simulated sweating skin. Most methods to assess the thermal and evaporative resistance of a textile material involve measures under a steady state of equilibrium. Because the results from these types of test methods are thought to be limited, Kim and Spivak (1994) decided to use a more realistic measure that would depict the changing conditions of a textile in actual use. The authors proposed that the sensitive nature and techniques of microhygrometry and thermometry could be used as new methods for assessing comfort behaviours of textiles as they are capable of closely simulating clothing in actual use.

In their research, Hatch, Barker, Woo, Radhakrishnaiah, Markee and Maibach (1990) measured several comfort related textile properties including air permeability, water vapour diffusion, wicking and the simultaneous measure of heat and moisture transfer. Hatch el al.'s research used a sweating hot plate with simulated sweating glands to supply water to a heated surface. In their study, three skin-clothing models were developed to simulate the following conditions: dry, wet without garment/skin contact and wet with contact. A guarded hot plate was used for the dry skin model, and a guarded sweating hot plate was used for the wet skin model. The guarded sweating hot plate with a spacer between the specimen and the sweating hot plate was employed to simulate a wet skin surface with no garment/skin contact. Using this equipment Hatch et al. were able to make predictions of comfort with relative confidence. The confidence in predicting comfort sensations from the research findings was mainly due to close simulation with actual clothing properties. Hatch et. al. predicted only small differences in perceived comfort of the experimental fabrics as they were similar in geometric and volumetric structure, and therefore, in water vapour, air permeability, dry heat and evaporative heat loss. However, the fabrics differed in their fibre content resulting in significant differences in liquid water transport properties. In a related study, by the same group of researchers, human wear trials were used to determine the relationship between subjective comfort measures and laboratory small scale test results (Markee, Hatch, Maibach, Barker, Radhakrishnaiah and Woo, 1990). The data collected from the laboratory tests were supported by the human wear trials.

Weder, Zimmerli and Rossi (1996) carried the simultaneous measure of heat and moisture transfer one step further by using a sweating moving arm to simulate the heat and moisture transfer under more realistic conditions of the human body. The sweating arm has the corresponding dimensions of a human arm. Both forearm and upper arm are capable of sweating in liquid or vapour form, and the forearm was designed to move at three different speeds. The sweating arm technique enables the researcher to examine the effects of different parameters on thermal and water vapour resistance. The various parameters that can be measured are: temperature, humidity, wind velocity, sleeve widths, sleeve openings and pumping effect of the movable forearm.

Few researchers have studied the protective and comfort properties of clothing together. Some researchers believe that it is not possible to separate protection and comfort due to the fact that comfort has an influence on protection and vice versa (Zimmerli and Weder, 1997). In Zimmerli and Weder's study a sweating torso was developed for a more realistic simultaneous measure of protection and comfort properties. The cylinder developed by Zimmerli and Weder has the dimensions of a human trunk. The cylinder apparatus is constructed of different material layers corresponding as close as possible to the thickness, heat capacity and thermal conductivity of the layers in human skin. Temperature sensors are mounted at 20 locations in the different layers. There are also 36 sweating nozzles evenly distributed over the surface of the cylinder. The torso is placed in an environmental chamber that allows the measurement of the combined influence of outside thermal hazards and internal physiological conditions of the human body on the overall performance of the protective clothing.

Zimmerli and Weder carried out their tests with the torso to evaluate sleeping bags in cold environments. The results obtained from their testing of sleeping bags were qualitatively in agreement with those from practise tests with human subjects. However, the authors acknowledge that more work must be carried out to prove the quantitative agreement with real life experiences. Zimmerli and Weder also plan to test the torso when subjected to a source of radiative heat. The source of heat flux, still being constructed at the time they published their article, would correspond to one encountered by fire fighters when entering a burning building. In this type of test, the increase in core temperature of the torso covered with a given protective clothing assembly would be measured.

Researchers are now trying to simulate even more real life situations through the use of mannequins. With mannequin testing, one can examine heat and moisture transport properties of not only a fabric but also a specific garment assembly and design including air layers, openings and the effect of ventilation. An advantage of the mannequin is that it is able to move and simulate certain body positions such as standing, walking and lying. Various sites on the mannequin surface can also be tested to measure the insulation of specific garment areas (Williams, 1997).

Physical comfort properties of textiles may be tested by a variety of standard and proposed test methods. Questions still remain as to which method is the most appropriate, which methods will accurately estimate comfort, and which methods will correlate with subjective comfort ratings of wear trials. Many test methods measure the properties of heat transfer and moisture transfer separately. As Meinander (1988) suggests the phenomena of heat and moisture transfer have an affect on each other, therefore it is necessary to be able to measure these properties together.

Measuring Liquid Transport

It is generally thought that fabrics with acceptable liquid transport properties will demonstrate good comfort (Hatch et al., 1990). As a textile material transports liquids away from the body it reduces the sensation of wetness and allows more surface area for water to evaporate for heat loss. While performing at high levels of activity in hot environments, the body can put out as much as two to three litres of sweat an hour (Goldman, 1988). Therefore, liquid transport is especially important as it will facilitate quick drying and faster cooling (Hatch et al., 1990).

Some researchers have divided liquid transport of fabrics into two phenomena: wettability and wickability. In 1994, Ghali, Jones and Tracy contributed to the area of comfort assessment by measuring the comfort related textile properties of wetting and wicking. Ghali et al. studied the movement of liquid in fabrics using a capillary pressure technique to determine the wicking of a fabric, and a siphon test for liquid water permeability. Although each test method used a different technique to measure the same property, the results showed a high correlation. In their study, Ghali et al. did not attempt to make any predictions of the comfort rating of a given fabric. However, from the wetting and wicking results it is possible to compare and rank given fabrics for their ability to transport liquid.

Equipment was developed by Hussain and Tremblay-Lutter (1996) that specifically measures liquid penetration in textile materials. The Dynamic Absorbency Measurement Technique (DAMT) was designed to control conditions of initial contact between fabric specimen and liquid. The automated DAMT measures liquid movement by both transplanar and planar flow. Hussain and Tremblay-Lutter found that controlling the fabric/liquid contact it was possible to obtain reproducible absorbency test results. However, for absorption to occur there must be an affinity between the liquid and the absorbent material (Chatterjee, 1985). The property of fibre wettability or fibre surface energy is a controlling factor in absorbency.

Chromatic techniques have been developed by some researchers to measure the dynamic surface wetness of fabrics against colour standards (Scheurell, Spivak, and

Hollies, 1985). A simple technique was developed to study the movement of moisture using a sweating skin, simulated by a wetted chamois cloth heated to skin temperature. Moisture was supplied to the device by a water overflow to maintain a certain degree of wetness. In this study, colour changes associated with different moisture levels were rated by a panel of trained observers. Due to difficulties in calibrating the fabrics for colour change, and training the operators to judge colour changes, Scheurell et al. decided to evaluate colour change by matching with the painted standard chips of the Munsell Colour System. From previous research using human wear trials, they were able to conclude that moisture levels on the fabric surface measured by colour change appeared to be directly related to sensations of discomfort perceived by the wearers of the fabrics under sweating conditions.

Air Permeability and Other Textile Properties

In addition to thermal conductivity, research has also focused on air permeability as a measure of thermal comfort of clothing. Air exchange plays an important role in thermal comfort and minimizing heat stress associated with clothing. The rate at which air moves through the clothing/body microenvironment space is determined by the following factors: air permeability of the fabric, design of the garment, body movement, wind speed and volume of the microenvironment (Crockford, 1988).

Cheng and Cheung (1994) used a Warmth Retaining Tester (Thermal conductivity, ASTM D1518) to measure the time required for heat to transfer from a warm, dry horizontal flat plate up through a layer of fabric to a relatively cool atmosphere. Along with heat transfer they also studied air permeability. The Automatic Air Permeability Tester (ASTM D737) was used to measure the amount of air capable of passing through a fabric. They found that porosity was the main factor affecting a fabric's air permeability. Interfibre and interyarn spaces contribute most to fabric porosity.

In their study of the effects of barrier finishes on aerosol spray penetration and comfort of protective clothing, Hobbs, Oakland and Hurwitz (1986), measured the physical properties of fabric density, weight, thickness, water vapour diffusion and air permeability to indicate fabric comfort. ASTM D737 was used to measure the air permeability of textile fabrics. A fabric air permeability of $4.4\text{X}10^{-3}$ (m^3 of air/s)/m^2 was defined as impermeable and an indication of low comfort in a work situation. The purpose of their research was not only to identify fabrics that would resist penetration of aerosol sprays, but would also provide a high level of comfort to the wearer.

It is believed that both thermal transmittance and air permeability contribute to the overall insulation effectiveness of a fabric, and therefore it would be beneficial to measure these properties simultaneously (Epps and Song, 1992). Epps and Song studied these properties concurrently in order to evaluate the combined effects of yarn structure and related fabric structure on both thermal transmittance and air permeability. Their research findings suggested that air spaces (affected by fabric thickness, yarn tex, yarn twist, fabric count, cover factor, and bulk density) within fabrics were associated with high air permeability and low insulation. This study emphasizes the importance of choosing fabrics which optimize either thermal transmittance or air permeability depending on the climate in which the clothing will be worn. For example, protective clothing worn in high temperature climates should facilitate the transfer of excess body heat by being made from fabrics with high thermal transmittance and high air permeability.

Correlation Between Wear Trials and Physical Laboratory Testing

Some researchers feel that studying humans is the only way to truly measure comfort. In a controlled wear trial with human subjects, the following physiological data may be measured: core body temperature, surface body temperature, heart rate, and sweat loss. Inhaled and exhaled air from subjects may also be examined for O_2 use and CO_2 production. In addition to objective measures, subjective information about perceived comfort may be collected by having the participants respond to various types of standardized instruments.

In several cases, wear trials have been compared with physical laboratory tests (Morris, Prato, Chadwick, and Berneauer 1985; Markee et al., 1991; Markee et al., 1990; Holmer, Nilsson, and Meinander, 1996; Williams, 1997; and Barker and Scruggs, 1996).

Morris et al. (1985) designed a wear trial to evaluate physiological and subjective measures of human subjects in warm up suits. The researchers also performed the following physical tests on the test fabrics: Drop Absorption (AATCC Test Method 39-1980), Static Absorption (AATCC Test Method 21-1978), Vertical Wicking (Skinkles 1949 method), Vapour Transport (an adoption of various procedures) and Rate of Liquid Transport (a variation of the same method used for vapour transport). The findings suggested that only two small scale test methods could predict the subjective evaluations of the warm up suits: liquid transport test and drop absorption. This may be accurate given that the mechanism of moisture transport is complicated, and that laboratory tests may not simulate the complex interaction between clothing and the individual.

Markee et al. (1991) also performed wear trials, and compared their subjective results with physical test measurements. The wear trials specifically considered the influence of fabric on skin wetness. In addition to these tests, heat and moisture transfer of the fabrics were analysed using three methods: Kawabata Thermolabo, wicking and air permeability tests. The three different garments tested were found to be similar in their measures of comfort related factors (heat transfer, wicking and air permeability). The findings from the wear trials correlate with the physical tests as the test garments did not cause significant differences in the physical responses of the subjects. In this case the predictions from the physical tests were valid, and substantiated by the human wear trials.

Further research has been carried out to develop a technique to compare the performance of clothing under actual wear conditions. Holmer, Nilsson and Meinander (1996) evaluated clothing heat transfer with a dry, standing and walking mannequin, a standing, sweating mannequin, and human wear trials. Measurements of a walking, sweating mannequin were not taken as the technology did not exist at that time for the simultaneous measurement of dry and evaporative heat transfer. Holmer et al. were able to conclude that the thermal insulation data from the walking and sweating mannequin were in agreement with the measurements from the human subjects.

Williams (1997) also compared the results of various tests including the control dish, togmeter, two variations of the skin model, and sweating/thermal mannequins to human wear trials. Williams found that small scale test measures directly compare to mannequin measures when garment openings were taped on the mannequin. With the tape, the garment became a sealed clothing system and the effects of ventilation were minimized. Under these conditions, when testing fabric effects only, less costly, small scale test methods gave the same results as more complex expensive mannequin testing.

Barker and Scruggs's (1996) research discusses the relationship between objective measures and human comfort responses to the test materials. The Kawabata Evaluation System was used to measure fabric mechanical and surface properties that predict clothing comfort. In addition, a sweating skin apparatus was used to measure heat and moisture transfer through test materials as well as the BS 3424 method to measure vertical wicking. Human responses to the fabric tactile properties and garment comfort were assessed in controlled laboratory trials. In general, the researchers found that thermal resistance was related to fabric thickness and evaporative heat transfer was controlled by fabric porosity. Their research indicated that there was little difference in the thermal resistance and the water vapour permeability ratings among all the single layer woven fabrics. Therefore, they concluded that thermal resistance and moisture vapour permeability were not the most important factors contributing to perceived comfort of the fabric systems. They found the most useful measures for explaining differences in comfort perceptions were: fabric weight, mechanical, surface and liquid transport properties.

Hassenboehler, Nigg, and DeJonge (1988) developed a 10 point rating scale to evaluate comfort based on physical textile properties. The fabric ratings were then verified with human wear trial data. The researchers evaluated the comfort properties of the fabric systems using a test battery consisting of thermal transmittance with simultaneous moisture transport (using a mixed flow transmittance tester with added water reservoirs), fabric wind penetration potential and clothing radiant temperature (Clort). Wind penetration potential was used to characterize the potential benefit of breezes to improve the thermal comfort of the fabric. The lower the Clort value the lower the heat stress on the skin. The researchers graded the performance of the fabrics in each test on a 10 point scale. Higher points were awarded to fabrics that relieved or lowered heat stress. These thermal comfort scores were then compared to field test results. Subjects rated the coveralls from 1 to 10, a score of 1 being the lowest in the categories of: comfortable, temperature, pleasant, ventilation, acceptable and satisfied. The research findings indicated that the subjective comfort ratings for the four fabrics in the study reflect the same results as the mean skin temperature taken from the subjects during the trial. In general, the effect of heat, moisture and air transport on thermal comfort were found to provide a good indication of actual human comfort as evaluated from field trial testing.

Development of Comfort Models and Indices

When workers are required to wear protective clothing it is essential that the protective equipment offer a sufficient level of protection. It is also important that protection is not impeded by increased physiological and mental strain, impaired performance or increased discomfort as a result of the protective clothing. As previously stated in this review, thermal balance depends on equal heat production and heat loss from the body. Factors that will affect this balance are a person's metabolism, thermal properties of the clothing worn, and the ambient conditions (Holmer, 1995). Models and indices have been developed to predict the interaction among these factors and their effect on the body. The main problem encountered with protective clothing is the impedance of evaporative heat exchange (Holmer, 1995). It is therefore essential that a predictive model or index include evaporative resistance of clothing.

Indices have been derived from four common approaches: 1) physical indices based on one or more of the physical factors of the environment (temperature, humidity, and air motion), 2) subjective indices based on assessments of thermal sensations, 3) 'rational' indices based on human heat balance equations, and 4) physiological indices based on physiological strain (Goldman, 1988). The fourth approach to indices development takes into account adjustments for differences in clothing.

Heat stress caused by the wearing of particular clothing is poorly understood. The most promising approach to resolve the problem of heat stress caused by clothing is through predictive modelling. Modelling builds on the concept that heat strain results from an imbalance between the demands imposed on the individual by the activity, climatic conditions, and the capacity of the worker to eliminate the heat load as modified by clothing (Goldman, 1988). The benefit of the predictive model for the garment manufacturer is that it is based on few simple laboratory tests and describes a clothing ensembles' comfort characteristics under all possible wear and climatic conditions (Umbach, 1988).

Heat Indices

The purpose of McCullough and Jones' (1984) study was to first expand the data base of insulation (Clo) values for garments worn indoors, measured using a standing, electrically heated mannequin, and to develop and compare different methods for estimating clothing insulation.

The thermal insulation provided by clothing has been predicted with accuracy using the four following methods. Garment insulation values can be easily predicted from fabric thickness, and the amount of body surface area covered by the garment. Ensemble weight and the amount of body surface area covered by different numbers of fabric layers are also good predictors of clothing insulation. Summation formulas which estimate ensemble insulation from the sum of the Clo values of the component garments is a another method that gives relatively accurate predictions of ensemble Clo values. However, McCullough and Jones found that the computer model they developed, which addresses dry heat loss only, generated the most accurate predictions of ensemble insulation.

McCullough and Jones' computer model divides the body into 12 segments. The skin temperature of each segment was determined by averaging the value for that segment for a wide range of clothing. The temperatures were not changed for different clothing systems, therefore skin temperature was constant in the model for all ensembles. The insulation provided by trapped air layers was quantified in the computer model. Air layer thicknesses in the clothing systems were determined by measuring clothing circumferences at different locations on the body for successive layers of clothing in an ensemble. The procedure set out for measuring the clothing circumferences was outlined as follows: First the nude body circumferences were measured at given points on the mannequin. Then the inner garment of the ensemble was put on the mannequin. The circumference was measured with a string, taking care not to compress the garment. Another person repeated the measurement and the average of the two was recorded. The next garment in the ensemble was put over the first and the circumferences were measured again with the string method. This continued until all circumference measurements of each layer were measured. The air layer thicknesses in the ensemble were determined by subtracting the fabric thickness and smaller circumference from the larger circumference.

McCullough and Jones found that values from their computer model were in agreement with thermal insulation results taken from a thermal mannequin. The computer model is used not only to estimate overall insulation or body heat loss, but it will also give an indication of how specific changes in the composition of an ensemble (design, fit, fabric thickness) will affect the insulation provided. The computer model is simple and easy to use, however the measurement method for air layer thickness is a time consuming process.

Computer Models to Predict Fabric Performance in Small Scale Tests

Farnworth (1986) developed a numerical model of the combined diffusion of heat and water through textile materials to simulate actual fabric measurements on a sweating guarded hot plate. The model combines conductive and radiative heat flow, as well as diffusion of water vapour through a multi-layer fabric system. The model takes into account effects of condensation, absorption and evaporation of water within fabric layers. The computer model is capable of producing results immediately, without the high cost of equipment, and an environmental chamber for controling test variables. Different variables, such as ambient and test surface temperatures, relative humidity, sweat rate and duration, number of fabric layers and their thicknesses can be manipulated in the model. However, this model is limited to situations where there is no convective air flow. In a real life situation, the model would then only apply to clothing with a wind proof outer layer or clothing worn in still air conditions. The qualitative agreement between the computer model and the sweating guarded hot plate apparatus is good. All the features of the experimental curves are predicted by the calculations, but the numerical agreement is not exact. In general, dry heat loss is predicted accurately, but evaporative heat loss when sweating starts is underestimated and fabric surface temperature predictions are slightly high.

General Predictive Models

The prediction of comfort and the effects of clothing on the assessment of thermal burden is not a new concept. This area has been studied extensively by many researchers over the years. Martin and Goldman (1972) were two of the early scientists who studied the prediction of heat stress imposed on soldiers working in a hot environment while wearing three different types of chemical protective clothing systems and one standard US combat uniform. Clo units of thermal insulation and permeability index values were evaluated using both a dry and wet standard hot plate procedure to measure physical properties of the fabric systems. A heated sweating copper mannequin was used to measure insulating and evaporative properties of the uniforms. Physiological wear trials were then performed to evaluate the accuracy of the rank ordering and the heat storage predictions.

In Martin and Goldman's study, a computer model with human thermal measurements was programmed with values from physical textile measures. The tolerance range for wear of the uniforms was then calculated as a function of these values and wearer work load, ambient temperature, vapour pressure, air movement and solar load. The findings of their research confirmed the rank ordering of the uniforms in terms of heat stress, however, actual values of heat energy storage were below those predicted from laboratory measures. Results indicated that the predictive energy balance equation failed to incorporate important factors present in human wear trials such as air motion produced by wind and subject movement. After this study, corrections were made to the computer programme to compensate for the error. Givoni and Goldman (1972) adjusted the insulation and vapour permeability indices to include considerations of wind and air movement generated during human activity.

Traditionally, predictive models and indices have focused on the diffusion of heat and water vapour. In addition to diffusion of heat energy and moisture, transport through a clothing system also involves convective air flows, and liquid water capillary wicking (Gibson, 1996). Most models are based on measurements at steady state conditions, however, humans rarely work at a sustained level of work, therefore steady state measures of the total heat energy and mass transfer through clothing are often inaccurate as they are often not applicable to real life situations.

Researchers have extended their approach to predictive models over the years. Gibson (1996) felt there was a need for comprehensive predictive models for clothing that included more than just vapour diffusion. The purpose of Gibson's study was to develop a model of energy and mass transport through porous hygroscopic clothing materials. The model accounts for the often neglected factors of sorption, condensation, evolution of heat, liquid water capillary wicking, and combined diffusion of heat and mass. Holmer (1995) emphasizes the importance of including the liquid water accumulation and transport in a predictive model as it is known that these factors are important when one is wearing a multi-layer clothing system and sweating heavily. When evaporated sweat condenses before escaping to the environment it will give off heat to the surrounding clothing layers. The performance of any clothing system is intimately linked to thermal properties of the human wearing the system, it is thus necessary to combine the behaviour of the clothing system with the human physiology of heat regulation.

Gibson developed a mathematical numerical model that included all major modes of energy and mass transport in clothing. Gibson used a modelling approach to develop a set of partial differential equations. The combination of these with an established human thermal physiological model provides the opportunity to examine clothing variables and determine their effects under various conditions of human work rates and environmental conditions.

The design process for protective clothing usually begins with the selection of a textile material based on steady-state properties determined from laboratory tests. Then thermal mannequins and/or controlled chamber trial testing is done to evaluate the dynamic interactions among the human, clothing and the environment. With his model, Gibson hopes to eliminate the need for extensive human wear trials by incorporating these interactions into a model to be evaluated at the material selection phase of the design process.

International Standards for Predicting Heat Tolerance and Comfort

There are three ISO (International Organization for Standardization) standards for assessing the effect of clothing on heat tolerance and comfort. There is a standard for moderate thermal environments (ISO 7730: 1994(E)) and two standards for hot environments (ISO 7243: 1989(E)) and ISO 7933: 1989 (E))). The ISO 7730 will determine whether a living or work place is thermally comfortable. The ISO 7243 and ISO 7933 will assess the heat load of workers who are exposed to high temperatures. There are many factors that affect heat tolerance but each standard takes into account clothing in various ways. Olesen and Dukes-Dobos (1988) explained how the effect of clothing is accounted for in each of the three ISO standards.

The ISO 7730 assesses thermal comfort in a moderate thermal environment where the degree of perspiration is minimal (ISO, 1994). Thermal discomfort is quantified by calculating the predicted mean vote (PMV) index. From mathematical equations the PMV can be calculated for different combinations of clothing (thermal resistance), human activity, air temperature, mean radiant temperature, air velocity and humidity. A PMV value of 0 will indicate that combination of activity, clothing and environmental conditions which will provide a thermally neutral sensation for a large group of people. To estimate the number of people in that large group who will feel too warm or cool, the predicted percentage of dissatisfied (PPD) can be calculated using the PMV value in an equation.

Olesen and Dukes-Dobos state that the ISO 7730 provides easily accessible information regarding the effect of clothing insulation on thermal comfort. The standard also includes tables for clothing insulation values for garments and clothing systems to be used in the equations. One limitation of this standard is that it assumes the clothing worn is water vapour permeable and environmental conditions are limited to a relative humidity of 50 %.

The ISO 7243 standard for estimating heat stress based on the WBGT (Wet Bulb-Globe Temperature) index is a simple standard that uses the work metabolism and the measurement of the natural wet bulb temperature, globe temperature and air temperature (dry bulb temperature). As far as effect of clothing is concerned in this standard, it is limited to workers wearing uniforms that have an insulative value of 0.6 Clo and are air and vapour permeable (ISO, 1989[a]). In many work situations, heavy, impermeable protective clothing must be worn, therefore, this standard would not be applicable. The ISO 7933 eliminates this problem; its equations take into consideration work intensity, climatic conditions as well as clothing insulation and vapour permeability.

The ISO 7933 uses the index of required sweat because it emphasizes the cooling efficiency of sweating and vapour resistance of clothing (ISO, 1989[b]). To calculate the index of required sweat the following factors are required: activity level of the person (metabolic heat production), thermal insulation of the clothing, saturated vapour pressure at the skin and four environmental parameters (air temperature, mean radiant temperature, air velocity and partial vapour pressure). Although this standard has great potential, Olesen and Dukes-Dobos point out that tables for insulation and vapour permeability values are not readily available for protective clothing which limits the use of this standard.

From research cited in this report, it is evident that comfort is a complex concept. Interactions between thermal properties and moisture transmission play a major role in the measurement and perception of comfort. However, researchers have yet to fully understand the role of physical laboratory tests and their relation to human comfort. By combining models of body motion, human thermal physiology and external environmental conditions, it is now possible to create three dimensional models of the human/clothing system (Gibson, 1996), thus an improved understanding of the area of comfort and clothing may be achieved. Models that estimate clothing performance are useful when the time, resources, and facilities for measuring these properties are not available.

Summary

All humans strive for a feeling of contentment and well being. Clothing will greatly affect a wearer's perceived level of comfort. The level of comfort depends on the ability of the textile material to transport heat and moisture away from the body. Clothing that does not dissipate excess heat and perspiration will create hazardous situations for the wearer such as heat strain and even death. Due to the fact that the textile properties described in this review contribute to human wear comfort, it should be conceivable to predict how a material will perform and ultimately affect comfort based on these properties. By measuring physical textile properties, and correlating these to human wear trials, it is possible to develop models or indices that will predict actual comfort.

Chapter 3

METHOD

The purpose of this research was to investigate physical textile properties that may affect the comfort of chemical/biological (CB) protective clothing and to develop indices that will estimate human comfort while the clothing is being worn. These estimates of comfort were based on physical textile properties of the CB fabric systems. This study was divided into two parts. The first part of the study consisted of the measurement of various physical properties of the CB protective fabric systems. The focus of the second part of the study was correlational analyses between data obtained in the first part and secondary wear trial data on human physiological and subjective comfort measures.

Part I

Experimental Design

An experimental research design was used to determine differences in comfort related properties among various fabric systems used in CB protective clothing for the Canadian Forces (CF). Laboratory experiments were used to measure the following dependent fabric variables: *thermal properties, resistance to water vapour diffusion, evaporative heat loss* and *air permeability*. The independent variables were the CB protective fabric systems.

Procedures

Fabric Sampling and Conditioning

All four CB protective fabric systems used in this study were supplied by the Department of National Defence. Each fabric sample was tested as received, and conditioned according to CAN/CGSB-4.2 No.2-M88 (CGSB, 1988^a) at 20°C ± 1°C and 65% ± 2% relative humidity for at least 24 hours before testing unless otherwise specified. Specimens were selected from each fabric sample so that no two specimens for any test contained the same warp and filling yarns.

A description of the fabric systems used in this research is outlined in Table 1. Fabric structure was visually assessed and defined as the type of construction, such as woven, non-woven or knitted. The following standard test methods were used to characterize the fabric systems. The mass per unit area was measured by weighing five die cut specimens with an area of 20 cm^2 according to test method CAN/CGSB-4.2 No.5.1-M90 (CGSB, 1990^a). Fabric thickness, under 1.0kPa pressure, was measured according to CAN/CGSB-4.2 No.37-M87 (CGSB, 1987). Fabric count was determined using CAN/CGSB-4.2 No.6-M89/ISO 7211/2-1984 (E): Determination of number of threads per unit length (CGSB, 1989^b) and CAN/CGSB-4.2 No.7-M88: Knitted fabric count - wales and courses per centimetre (CGSB, 1988^b).

Measurement of Dependent Variables

Various forms of *heat* and *moisture transfer* and *air permeability* were studied following standard and proposed standard test methods: CAN/CGSB-4.2 No.70.1-94: Thermal Insulation Performance of Textile Materials; Sweating Guarded-Hotplate (Farnworth and Dolhan, 1985); CAN/CGSB-4.2 No.49-M98 fourth draft: Resistance of Materials to Water Vapour Diffusion; the Van Beest and Wittgen (VBW) Resistance to Water Vapour Diffusion (Van Beest and Wittgen, 1986); CAN/CGSB-4.2 No. 36-M89: Air Permeability; and the Dynamic Absorbency Measurement Technique (Hussain and Tremblay-Lutter, 1996).

CAN/CGSB-4.2 No.70.1-94 Thermal Insulation Performance of Textile Materials (CGSB, 1994)[1]

The Heat Flow Measurement Apparatus measures the heat flow from a warm dry, constant-temperature hotplate through a textile material. Heat flow was measured through the test specimen alone with no still air layers. Two specimens of each fabric

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[1] Testing done at Mustang Survival Corp. 3810 Jacombs Rd, Richmond, BC, V6V 1Y6 (604) 270-8631

Table 1. Description of the Single Layer CB Protective Fabrics used in this Research

FABRIC CODE	COMPOSITION/FIBRE CONTENT FABRIC CONSTRUCTION	FABRIC COUNT (yarns/cm) (warp x weft)	MASS (g/m^2)	THICKNESS (mm)
OUTER FABRIC	plain weave 50% nylon/ 50% cotton Zepel B® water and oil resistant finish	24 X 20	174	0.41
INNER FABRICS				
1	carbon fibre knit laminated to a fire resistant cotton ripstop fabric with a white nonwoven back	ripstop 35 X 20 carbon knit wales = 17 courses = 15	304	0.72
2	polyester knit coated with carbon spheres and a white nonwoven back	wales = 17 courses = 18	304	0.75
3	carbon impregnated foam laminated to a nylon knit	wales = 8 courses = 14	383	2.69
4	carbon impregnated Lycra® knit	wales = 15 courses = 27	201.4	0.60
	100% polyester interlock knit underwear	wales = 20 courses = 13	155.4	0.69

system were cut to a size that completely covers the surface of the hotplate (60X60cm). Fabric specimens were conditioned in ambient room temperature and relative humidity prior to placement in the test apparatus. To ensure the specimens were not compressed between the hot and cold plates, plastic spacers, the average thickness of the test fabric were placed in the corners between both plates. The hot (bottom) plate and the cold (top) plate were adjusted to maintain a constant temperature difference. It was not possible to maintain the temperatures of the hot and cold plates according to the standard (35±1.0 °C and 12±1.0 °C). However, temperature was controlled to ensure an adequate temperature gradient between the plates (average plate temperatures for each fabric specimen are given along with results in Chapter 4). The acquisition of data began after the specimens were placed in the apparatus, at test conditions, for at least one hour. Measurements were recorded every minute for a minimum 30 minute period or until the assembly reached equilibrium. The thermal resistance ($m^2 K/W$), thermal conductivity (W/mK) and average top and bottom plate temperatures (°C) were calculated for each specimen.

Evaporative Heat Loss: Sweating Guarded-Hotplate[2]

A sweating guarded hot plate, placed in an environmental chamber, was used to study the phenomenon of evaporative heat loss through textile materials. The device (Figure 1) simulates the heat and moisture transfer that occurs at the skin surface. Three specimens of each fabric system were cut into 25.3 cm diameter circles. Fabric specimens were conditioned in ambient room temperature and relative humidity prior to placement in the test apparatus. The rate of heat loss from three specimens of each fabric system, was measured before, during and after a period of sweating. The sweating guarded hot plate consists of a guarded hot plate with 24 water feed lines. In order to spread the water evenly over the plate, a layer of thin absorbent paper (coffee filter paper) was taped directly onto the plate. The central and guard plates were both heated to and maintained at a temperature of 35 °C. The power required to maintain the plate at a constant temperature of 35 °C was measured and was equal to the rate of heat loss through the fabric system. The environmental test chamber was controlled at a temperature of 20 °C and 50% relative humidity. The fabric specimen was placed on the plate, over the coffee filter paper with a sample ring securing four corners.

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[2] Testing done at Mustang Survival Corp. 3810 Jacombs Rd, Richmond, BC, V6V 1Y6 (604) 270-8631

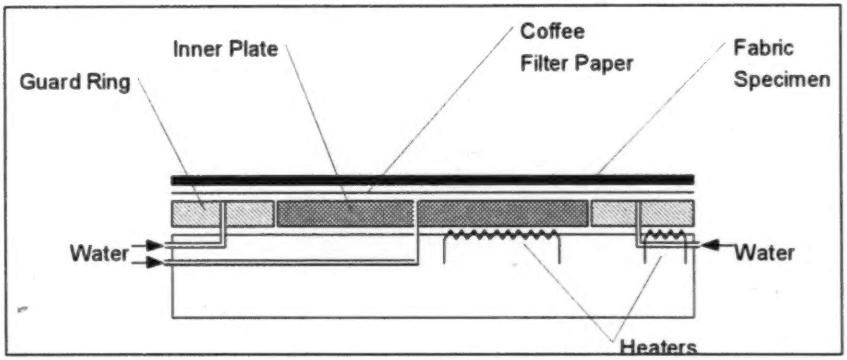

Figure 1. Schematic Diagram of Sweating Guarded Hot Plate (adapted from Farnworth and Dolhan, 1985)

The specimen was placed on the apparatus, in the specified test conditions, for 30 minutes prior to data acquisition. Once the initial conditioning period was over and the test period had begun, a computer recorded, at 20 second intervals, chamber and test plate temperatures, chamber relative humidity, and power supplied to the plate. The heat loss from the plate was measured with a sweat rate of 0 $g/m^2/hr$ for 30 minutes, then with a sweat rate of 360 $g/m^2/hr$ (considered to be a moderate sweat rate) for 30 minutes, and without sweating again until the specimen was dry (or dry heat loss rate at the beginning of the test was reestablished). The heat loss from three specimens during a period of sweating and non sweating was measured for each fabric system.

CAN/CGSB-4.2 No.49-M97 (draft revision) Resistance of Materials to Water Vapour Diffusion (CGSB, 1997)

This method determines the resistance of textile materials to water vapour diffusion by sandwiching a fabric specimen between two microporous films. One layer of film separates the specimen from a flow of dry air and the other film forms the bottom of a water dish. The loss of water from the dish over a given amount of time was used to determine the resistance to water vapour diffusion through the specimen and two microporous films. The resistance of the specimen was determined by the difference in the diffusion of water vapour from the apparatus with the specimen in place and without the specimen. The average water vapour diffusion resistance of four test specimens was reported in units of millimetres of equivalent still air.

Van Beest and Wittgen (VBW): Resistance to Water Vapour Diffusion[3]

An apparatus designed by Van Beest and Wittgen (1986) was used to measure the water vapour resistance of textile materials by sandwiching, without compression, a specimen between one microporous film and an absorptive layer (filter paper). The device (Figure 2) consists of a small air chamber covered with a microporous film that fits into the upper part of a water chamber with an absorptive layer. The specimen was placed between these chambers with the inside of the fabric system facing the absorptive layer. A spacer thickness of 6 mm was used consisting of a 2 mm spacer ring between the absorptive layer and the fabric specimen and spacer rings equal to 4 mm between the specimen and the air chamber. Prior to data acquisition, the specimen was placed in the apparatus, for at least 20 minutes, under test conditions with the water chamber filled and dry air flowing through the air chamber. The amount of vaporized water per unit of time was then measured from the pipette mounted on the apparatus and a stopwatch. The resistance of the specimen was determined by the difference in the water vapour diffusion

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[3] Testing done at Mustang Survival Corp. 3810 Jacombs Rd, Richmond, BC, V6V 1Y6 (604) 270-8631

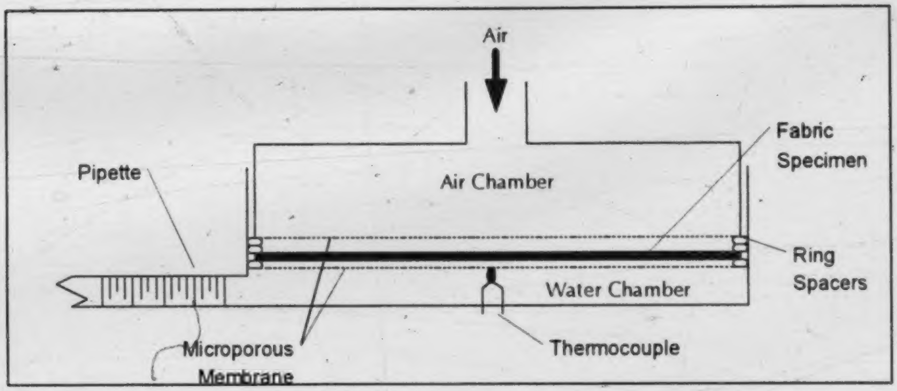

Figure 2. Schematic Diagram of VBW Method for Resistance to Water Vapour Diffusion (adapted from Van Beest and Wittgen, 1986).

through the apparatus with the specimen in place and the diffusion rate without the specimen. The resistance to water vapour diffusion, of four specimens for each fabric system, was reported in millimetres of equivalent still air.

CAN/CGSB-4.2 No.36-M89 Air Permeability (CGSB, 1989ª)

The Frazier air permeability machine was used to measure the amount of air (in cubic centimetres) passing through one square centimetre of fabric per second when the differential air pressures on opposite sides of the fabric was equal to 12.7 mm of water. The average of 10 determinations across each fabric system was expressed in cubic centimetres of air per square centimetre per second ($cm^3/cm^2 \cdot s^{-1}$).

Dynamic Absorbency Measurement Technique (DAMT)

The DAMT (Hussain and Tremblay-Lutter, 1996) is a device that measures the planar and transplanar absorbency characteristics of a textile material. An absorbency apparatus connected to a computer data acquisition package collects information on mass and liquid level changes during absorbency experiments. The duration of each run was set for 250 seconds, considered to be an adequate amount of time for water absorption to stabilize. The desorption test was also run for a period of 250 seconds to remove excess water from the fabric specimen after the completion of testing. To ensure good cell surface/fabric contact, a metal disk perforated with small holes was placed on the specimen and left in place during the remainder of the test. The absorbency rates of five 5 cm diameter-die-cut specimens were recorded and averaged to obtain the mean absorbency rate (g/sec).

Part II

In the second part of this research, Pearson's correlations were performed between data on physical textile properties of the fabric systems from Part I and secondary wear trial data on human comfort while the garment systems were being worn. Indices of the textile properties that best predict human comfort were then developed by performing multiple regression analyses of the data from both parts of the study.

Secondary Human Wear Trial Data

The human wear trial data that were analysed in this study include both subjective and physiological data from human subjects while wearing CB protective garments constructed from fabrics tested in this study. The physiological wear trial data were compiled by the Defence and Civil Institute of Environmental Medicine (DCIEM) in North York, Ontario, and the subjective comfort data by Defence Research Establishment Suffield (DRES). The subjective measures were collected during field trials and the physiological data collected during controlled chamber studies.

Description of McLellan, Bell and Dix (1994) Study to Assess Physiological Measures

The purpose of the study was to quantify and compare heat strain while wearing a new chemical defence vapour protective layer alone, under combat clothing (garment system 4) and while wearing the current CB protective clothing system (garment system 3). Only two out of three garment systems evaluated by McLellan et. al. (1994) were applicable to this study.

In total, 23 males participated in the study. All subjects were examined to ensure no medical contraindications to their participation in the experiments. Seven subjects were assigned to a light exercise group (walking on a treadmill at 1.11 m/s with a 0% grade for 15 minutes, then resting for 15 minutes); eight were assigned to moderate (continuous walking at 1.25 m/s with a 0% grade); and eight to heavy exercise groups (continuous walking at 1.33 m/s with a 3 % grade). Subject allocation to each exercise group was designed to minimize differences in fitness levels. A determination of peak aerobic power for each subject found that there were no significant differences among the three exercise groups.

All clothing trials were performed in a controlled environment chamber at 40°C and 30 % relative humidity. Heart rate, rectal temperature, and mean skin temperature were recorded every 5 minutes throughout the duration of the trial. A weighted mean skin temperature was calculated from a 12 point weighted equation. The trial was stopped when one of the following criteria first occurred: rectal temperature reached 39.3 °C, heart rate remained at or above 95% of maximum for 3 minutes, dizziness or nausea precluded further exercise or 5 hours had elapsed.

Permission for the use of the raw data from the study was granted by Dr. T. McLellan, Head of Applied Physiology Group, DCIEM (December 1998). New variables, maximum, maximum change and rate of change were computed for all three physiological measures for each participant. Heart rate (maximum) was defined as the maximum heart rate attained by the subject during the trial (max beats/minute). Heart rate (maximum change) was defined as the maximum heart rate attained minus the initial heart rate (△beats/minute). Heart rate (rate of change) was defined as the maximum heart rate attained by the subject divided by the time to reach the maximum heart rate (beats/minute•minutes^{-1}).

Mean skin temperature (maximum) was defined as the maximum mean skin temperature attained by the subject during the trial (max °C). Mean skin temperature (maximum change) was defined as the maximum mean skin temperature attained minus the lowest mean skin temperature (△°C). Mean skin temperature (rate of change) was defined as the maximum mean skin temperature attained by the subject divided by the time to reach the maximum mean skin temperature (max °C•minutes^{-1}). Rectal temperature (maximum) was defined as the maximum rectal temperature attained by the subject during the trial (max °C). Rectal temperature (maximum change) was defined as the maximum rectal temperature attained minus the lowest rectal temperature (△°C). Rectal temperature (rate of change) was defined as the maximum rectal temperature attained by the subject divided by the time to reach the maximum (max °C•minutes^{-1}). Tolerance time was defined as the total time the participant was able to continue the trial while wearing a given garment system. For statistical analysis, measures of heart rate, skin temperature, rectal temperature and tolerance time for each participant were entered into an SPSS data file along with physical textile property data from Part I.

Description of McLellan, Bell, Smith, Morris, and Miyazaki's (1997) Study to Assess Physiological Measures

The purpose of the study was to compare the heat strain associated with wearing the current CB ensemble (system 3) with new CB garments designed for use in hot environments. The study considered two new design concepts: an undergarment protective layer worn under operational clothing and a stand-alone garment design to replace the current CB ensemble worn over combat clothing. Only two of the garment systems evaluated were applicable to this study (garment systems 2 and 3). The stand-alone garment (system 2) consisted of separate barrier and outer shell materials sewn together to make a one piece garment (fitted coverall with integral hood). The barrier fabric of the garment system was composed of a polyester knit coated with activated carbon spheres. The outer shell material was a nylon/cotton fabric treated for liquid repellency. Operational clothing describes normal combat clothing worn over a T-shirt and briefs.

Eight male subjects wore each garment system in the experiment. The subjects alternated 45 minutes of walking on a treadmill (0% grade at 1.1 m/s and wind speed less than 0.1 m/s) with 15 minutes of seated rest for a maximum of 4 hours in an environmental chamber at 40°C and 30% relative humidity. All trials continued for a maximum of 4 hours or when rectal temperature reached 39.3°C, heart rate remained at or above 95% of the individual's peak value for 3 minutes, dizziness or nausea prevented further exercise, the subject asked to be removed or was removed by the investigator.

Permission to use raw data was granted by Dr. T. McLellan, Head of Applied Physiology Group, DCIEM, December 1998. As described for the 1994 physiological study, new variables maximum, maximum change and rate of change were created for each physiological measure of heart rate, mean skin temperature and rectal temperature. Data were entered into an SPSS file along with physical textile data from Part I.

Description of 1995 Field Trial to Assess Subjective Comfort

Subjective comfort data were compiled during a comparative subjective evaluation after wearing both a prototype undergarment (system 4) and the current Canadian CB Ensemble (system 3) while performing normal operational activities in warm climatic conditions (W. R. Davis Engineering Limited, 1995). A wear assessment was also included in the study in order to inspect the undergarment components before and after the user trial. The wear trials were performed in warm climatic conditions. During the first two weeks in August 1994, a mean temperature of 24°C and a mean relative humidity of 90% was attained in Victoria, BC when the trial was conducted.

The prototype undergarment system (system 4) consisted of the following components: one white underwear top, one white underwear bottom, one pair of white glove liners, one charcoal impregnated top, one charcoal impregnated bottom, one pair of charcoal impregnated socks, a pair of charcoal impregnated gloves, and charcoal impregnated hood. The white undergarment (100% polyester) layer was worn next to the skin, the charcoal impregnated Lycra® on top of the white layer, and then the user's operational dress as the outer layer. The in-service CB ensemble (system 3) consisted of a one piece coverall composed of a charcoal impregnated foam and a water and oil resistant outer layer worn over operational clothing.

Two questionnaires were created for this study to enable subjects to provide subjective feedback with respect to acceptability of the two clothing systems. The questionnaires addressed subjective comfort while wearing the two garment systems in the open state: CB coveralls on, zipper and velcro fasteners open, hood up or down, CB boots on, and CB gloves and respirator carried. For the undergarment system, all items of the protective suit were worn excluding the respirator, hood and gloves. Three questions of interest in both questionnaires (Appendix A1 and A2) used a rating scale from 1 to 7, with descriptors of "very cold vs. very hot", "very comfortable vs. very uncomfortable" and "very dry vs. very wet". Trial participants responded to the three items measuring comfort based on completing duties that required both low and strenuous physical effort.

The questionnaires were completed by two different groups. With the exception of one subject, all of the trial participants were males. The Navy user trial consisted of Damage Control School students and staff who completed the questionnaire at the end of the trial after wearing only the prototype undergarment system. The Air Force user trial consisted of ground support technicians who completed the appropriate questionnaire after having worn each protective clothing system. Only the latter trial was used in this study.

Permission to use raw data was granted by Julie Tremblay-Lutter, Head of Personal Protection Group, DRES, December 1998. Once the data was received it was entered into an SPSS data file along with physical textile data compiled from Part I of this study. Two new variables (total comfort during low physical effort and total comfort during strenuous physical effort) were computed by summation of the three descriptors of "very cold vs. very hot", "very comfortable vs. very uncomfortable" and "very dry vs. very wet".

Description of 1998 Field Trial to Assess Subjective Comfort

Comfort data were compiled during September 1998 during an evaluation of three prototype hot weather CB garment systems during the course of a military training program in Gagetown, New Brunswick. A wear assessment was also included in the study in order to inspect and evaluate the garment components after the completion of the user trial.

Two of the garment systems evaluated were applicable to this study. Both hot weather garment systems (systems 1 and 2) consisted of separate barrier and outer shell materials sewn together to make a one piece garment (fitted coverall with integral hood). The barrier fabric of garment system 1 was composed of a carbon fibre knit laminated to a ripstop fabric. The barrier fabric of garment system 2 was composed of a polyester knit coated with activated carbon spheres. The outer shell material of both systems was a nylon/cotton fabric treated for liquid repellency.

A questionnaire was developed in French and English to enable subjects to provide subjective feedback with respect to acceptability of the garment systems. Comfort was assessed using seven point scales consisting of 10 bi-polar adjective pairs (Appendix A3). In total, forty subjects wore one garment system each and completed the questionnaires at three different times during the trial, once at the beginning (pre-trial questionnaire), the second five days into the trial (mid-trial) and the third at the end of the trial (post-trial). Data from the pre-trial questionnaire were not used in the analyses for subjective comfort in this study. On average, garment system 1 and 2 were worn for 126.7 hours (7.8 days) and 130.1 hours (7.9 days) respectively.

The raw data from the 1998 Gagetown CB hot weather garment durability wear trial was requested from the Defence Research Establishment Suffield. Once permission to use raw data was granted by Julie Tremblay-Lutter, Head of Personal Protection Group, DRES, December 1998, it was entered into an SPSS data file along with physical textile data compiled from Part I of this study for statistical analysis.

Development of the Comfort Indices

Comfort indices were developed by performing multiple linear regression analysis of all physical textile properties separately with subjective comfort scores and physiological measures. Those physical textile properties that were found not to have a significant contribution to comfort were dropped from the models. Those with significant contributions were included in the indices. The indices developed from the analysis are called the Estimated Subjective Comfort (ESC) Index and the Estimated Physiological Comfort (EPC) Index.

The Estimated Subjective Comfort (ESC) Index is used to calculate the estimated level of perceived comfort experienced by an individual based on the physical characteristics of the garment fabric system. The EPC Index estimates the physiological comfort of an individual based on physiological measures of the human body and physical textile properties. The ESC and EPC Index were developed knowing the total subjective comfort score, physiological measures and the fabric system's physical textile properties, but are intended to predict human comfort with knowledge of only textile variables.

Statistical Analysis

The following statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) version 8.0 at the University of Alberta, with a significance level set at $p < .05$ for hypothesis testing.

1. Descriptive statistics were used to summarize and describe the different CB protective fabric systems.
2. One-way analysis of variance (ANOVA) with Dunnett T3 pairwise multiple comparisons were performed to determine which fabric systems differ significantly from each other for each dependent variable.
3. Two-way ANOVA was performed to determine if there were effects of garment

system and exercise level or interaction effects on the physiological data for garment systems 3 and 4. Independent-samples t-tests were performed to determine if there were significant differences in physiological measures between garment systems 3 and 4. Pearson's correlation analyses were performed to determine the strength of linear associations between all pairs of physiological measures.

4. Independent-samples t-tests were performed to determine if the physiological measures differed significantly between garment systems 2 and 3.
5. Independent-samples t-tests were performed to determine whether subjective comfort data differed significantly between garment systems 3 and 4.
6. Independent-samples t-tests were performed to determine whether subjective comfort data differed significantly between garment systems 1 and 2.
7. Pearson's correlation analyses were conducted to test for significant relationships between data from each of the six small scale test methods and physiological and subjective data from the human wear trials.
8. Multiple linear regressions were used to develop comfort indices by determining which combinations of the six textile properties best predict physiological and subjective comfort measures.

Summary

The first part of this research was conducted as an experimental design using six different laboratory tests to study the physical textile properties of the different fabric systems. The independent variable was fabric system. The dependent variables were the properties of *thermal resistance*, *resistance to water vapour diffusion*, *evaporative heat loss* and *air permeability*. The second part of this research was the development of predictive comfort indices based on data obtained from Part I and secondary human wear trial data.

Chapter 4

RESULTS

Results of the small scale tests in Part I of this study, are presented for multi-layer fabric systems. Results from the second part of this study comprise a summary of statistical analyses of the human wear trial data and the development of comfort indices. To test null hypothesis one, physical textile data were analysed in their raw form. To test null hypothesis six to nine, physical textile data were randomly assigned to wear trial data to make an identical number of cases for each dependent and independent variable.

Effect of Fabric system on Physical Textile Properties

> Ho_1: There are no significant differences in physical textile properties among the CB protective fabric systems.

Null hypothesis 1 was rejected. One-way ANOVA and Dunnett T3 multiple comparison test (Table 2) found significant differences among the fabric systems' physical textile properties. Only measures of thermal conductivity were found not to differ significantly among fabric systems.

Air permeability. One-way ANOVA results show that fabric system 1 (knit carbon fibre) had the lowest air permeability. Fabric system 3 (carbon foam) had an air permeability value almost twice that of system 1. Systems 4 and 2 did not differ significantly from one another and also had the highest air permeability of the systems tested.

Water vapour diffusion resistance. Water vapour diffusion resistance was measured using two different test methods (CGSB method 49 and VBW). Although both tests measure the same phenomenon they did not give the same numerical values of water vapour diffusion resistance. However, both test methods gave close to the same rank order. For the CGSB method, fabric systems 1 and 2 had the lowest resistance and did

Table 2. Summary of Mean Physical Textile Properties of the CB Protective Fabric Systems

FABRIC SYSTEM CODE	Air Permeability ($cm^3/cm^2 s^{-1}$) n=10 (Std.Dev.)	CGSB Resistance to Water Vapour Diffusion* (mm of still air) n=4 (Std.Dev.)	VBW Resistance to Water Vapour Diffusion** (mm of still air) n=4 (Std.Dev.)	Thermal Resistance (m^2 K/W) n=2 (Std.Dev.)	Thermal Conductivity (W/mK) n=2 (Std.Dev.)	Evaporative Heat Loss (W/m^2) n=3 (Std.Dev.)	Absorbency Rate (g/sec) n=5 (Std.Dev.)
1	16.35^{a} (2.06)	2.52^{a} (0.24)	2.93^{b} (0.28)	0.0210^{a} (8.49×10^{-5})	0.0559^{a} (8.65×10^{-3})	307.98^{b} (18.98)	0.02^{c} (0.005)
2	47.61^{c} (1.18)	2.75^{a} (0.06)	1.21^{a} (0.12)	0.0211^{ab} (7.21×10^{-4})	0.0503^{a} (1.71×10^{-3})	328.86^{b} (5.94)	0.01^{b} (0.000)
3	31.64^{b} (2.27)	6.58^{c} (0.62)	4.75^{ba} (1.55)	0.0615^{c} (6.39×10^{-4})	0.0439^{a} (4.58×10^{-4})	234.55^{a} (17.37)	0.00^{a} (0.000)
4	46.90^{c} (3.91)	4.25^{b} (0.13)	2.96^{b} (0.10)	0.0303^{b} (3.18×10^{-4})	0.0428^{a} (4.45×10^{-4})	316.10^{b} (40.53)	0.09^{d} (0 .014)

[a, b,etc] In each column, means with the same letter indicates homogenous subsets (highest and lowest means are not significantly different) when subjected to Dunnett T3 pairwise multiple comparison test ($p<.05$).

*CAN/CGSB-4.2 No.49-M97 (draft revision) Resistance of Materials to Water Vapour Diffusion

** Van Beest and Wittgen (VBW): Resistance to Water Vapour Diffusion not differ significantly. Fabric system 4 had a significantly higher resistance than 1 and 2 but was significantly lower than system 3. For the VBW method fabric system 2 was significantly lower than all other systems except for system 3. Fabric systems 1, 3 and 4 were not significantly different when tested with Dunnett T3 pairwise multiple comparison tests.

Thermal resistance and conductivity. Measurements of thermal resistance and thermal conductivity were both determined by using a Heat Flow Measurement Apparatus. Values for thermal conductivity were not significantly different among the fabric systems. However, the fabric systems did differ on their values of thermal resistance. Thermal resistance was not significantly different for systems 1 and 2. Measures of thermal resistance for system 2 and 4 were not significantly different from each other, but were significantly lower than for system 3 which had a thermal resistance twice as high as system 4, and almost three times that of systems 1 and 2. Table 3 shows mean thermal resistance conductivity and top and bottom plate temperatures for each fabric system.

Table 3. Mean Thermal Resistance and Thermal Conductivity and Top and Bottom Plate Temperatures for Each Fabric System

Fabric System Code	Thermal Resistance (m^2K/W) n=2	Thermal Conductivity (W/mK) n=2	Average bottom plate temperature (°C) n=2	Average top plate temperature (°C) n=2
1	0.0210	0.0559	22.0054	27.7473
2	0.0211	0.0503	25.4963	20.3904
3	0.0615	0.0439	32.1326	18.5285
4	0.0303	0.0428	28.7129	20.9153

Evaporative heat loss. A typical example of heat loss data before, during and after the period of sweating is shown in Appendix B. A plot of log watts versus time was used to determine a time constant for the transient response of heat loss from the plate (personal communication, Dr. J. D. Dale, 27 November 1998). Three times the time constant was determined to be the point at which evaporative heat loss stabilizes after sweating commences. For each fabric system the time constant was determined by using one representative output data file, unless the heat loss curves for the specimens of a given fabric system differed significantly, in which case a separate time constant was determined for each specimen. The time constant was unique for each fabric system and would depend on the rate at which the fabric was able to retain or dissipate the heat generated from the plate.

In general, all fabrics exhibited an increase in heat loss when sweating started. When sweating ceased, all fabric systems experienced a decrease in heat loss and returned to their original dry heat loss as before sweating started. The evaporative heat loss for system 3 was significantly lower (235 W/m^2) than for the other systems. Not all of the water escaped through fabric system 3 immediately. After sweating had stopped, evaporation continued for an average of 2456 seconds when the plate and fabric dried completely, at which point the heat loss returned to its dry value. System 3 was the thickest fabric system tested, composed of a carbon foam which tended to expand in the presence of moisture, thus expanding the air layer and reducing the evaporative heat loss.

The evaporative heat loss from fabric systems 1, 2 and 4 were found not to differ significantly. However, of these three systems, fabric system 2 had the highest average evaporative heat loss value (329 W/m^2). When sweating began there was a steep rise in heat loss which tapered off into a more gradual rise until sweating had ceased. Fabric system 2 took an average time of 1686 seconds to return to its dry heat loss value which was considerably faster than system 3, but not as fast as system 4. When system 4 was observed during the sweating period, heat loss rose smoothly and rapidly to an average steady rate of 316 W/m^2.

Dynamic Absorbency Measurement Technique (DAMT). An absorbency rate in grams per second was measured using the DAMT apparatus. Fabric system 3 did not initiate water absorption at any time during the test period. The fabric sample was laundered according to CAN/CGSB-4.2 No.19.1-M90 test option #2 (CGSB 1990^b) to remove any residual substances from the fabric surface that would affect absorbency or initial wetting of the fabric specimen. Test option #2 of the method was chosen as it was appropriate for textiles that are expected to withstand repeated washing at moderate temperatures (50 °C) in a home or commercial laundry machine. Laundering failed to help initiate moisture absorption for fabric system 3. As a result fabric system 3 had an absorbency rate of 0 g/sec. Fabric systems 1, 2 and 4 were tested as received.

Typical absorption curves for fabric systems 1, 2 and 4 are shown in Figures 3, 4 and 5. System 4 had the highest absorbency rate. Instant initiation of water absorption by system 4 is evident by the steep absorption curve which quickly levels once water absorption stabilizes. Fabric system 1 had the second highest absorbency rate. Fabric system 2 had a significantly lower absorbency rate than both systems 1 and 4. Specimens for systems 1 and 2 had similar absorption patterns, however, system 2 took longer to initiate water absorption. Once initiated the absorption curve for both fabrics depicted a slow gradual increase in water uptake by the specimen. Time to stabilize water absorption for systems 1 and 2 was also longer than for system 4.

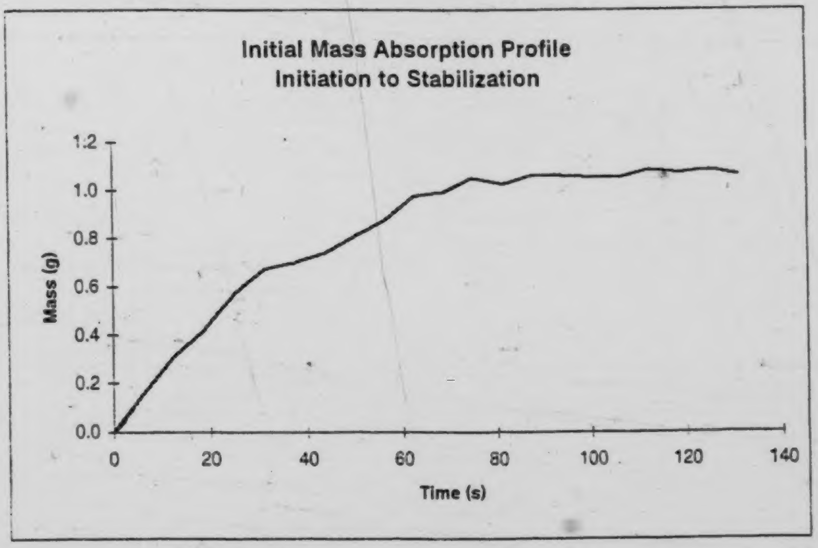

Figure 3. Typical DAMT profile illustrating absorption for fabric system 1.

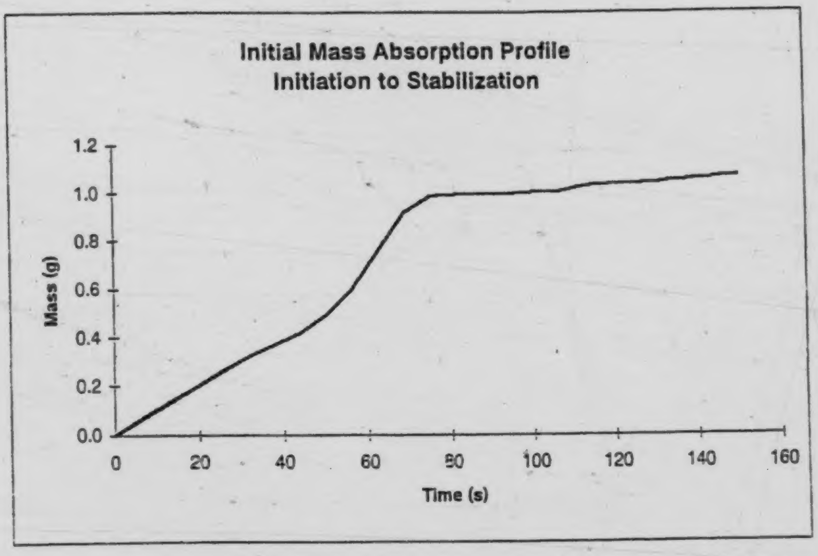

Figure 4. Typical DAMT profile illustrating absorption for fabric system 2.

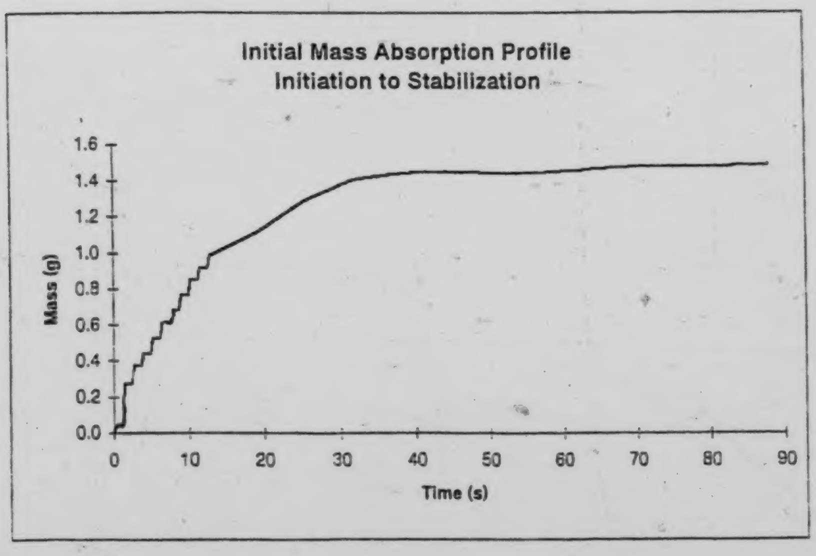

Figure 5. Typical DAMT profile illustrating absorption for fabric system 4.

Effect of Garment System and Exercise on Physiological Measures (Garment Systems 3 and 4)

Pearson's correlation analysis was used to determine the strength of linear associations among the physiological measures for each exercise level (Appendix C1, C2, C3). This analysis combined the physiological measures of the subjects for both garment systems. Correlation analyses were conducted to assess the possibility of combining the physiological measures into smaller subsets or an index for ease of statistical analysis. Factor analyses were performed, however, no such subset of variables was obtained. The correlation analyses were also helpful in explaining results of other analyses. Correlation coefficients were different for all three exercise groups and ranged from -.006 to .925 for light intensity; .034 to .848 for moderate intensity; and -.017 to .845 for heavy intensity exercise.

> Ho_2: There are no significant differences in physiological measures from human wear trials between CB protective garment systems 3 and 4 at each exercise level.

Null hypothesis 2 was rejected. Table 4 summarizes main effects of garment system and exercise level and interaction effects found by two-way ANOVA for each dependent variable. Mean heart rate, mean skin temperature and rectal temperature (rate of change, maximum and maximum change) of the subjects at each level of exercise for the two garment systems are compared in Table 5.

Heart rate. Two-way ANOVA's (Table 4) found significant main effects of exercise level and garment system, but no interaction effect for rate of change in heart rate; a significant main effect of exercise level for maximum heart rate, but no main effect of garment system or interaction effect; a significant main effect of exercise level on the maximum change in heart rate, but no main garment system effect, or interaction effect. Independent samples t-tests were performed at each exercise level separately to determine

Table 4. Summary of Two-way ANOVA: Effect of Garment System and Exercise Level on Physiological Measures (F-Statistic)

	Main Effects		Interaction
Dependent variables	Garment system	Exercise level	Effects
Heart rate			
(rate of change)	9.33*	75.020*	.202
(maximum)	0.26	8.34*	0.27
(maximum change)	0.09	6.72*	0.17
Mean skin temperature			
(rate of change)	24.05*	58.50*	0.46
(maximum)	12.88*	0.61	0.64
(maximum change)	1.30	0.05	0.63
Rectal temperature			
(rate of change)	12.21*	67.54*	0.31
(maximum)	0.32	0.23	0.23
(maximum change)	0.69	0.48	0.00
Tolerance time	41.50*	120.50*	17.79*

*significance level p<.01

Table 5. Independent Samples T-test: Mean of New Variables Created from McLellan et. al. (1994) Study

	Light Intensity Exercise		**Moderate Intensity Exercise**		**Heavy Intensity Exercise**	
	Garment System		Garment System		Garment System	
New Variables	**3**	**4**	**3**	**4**	**3**	**4**
Heart Rate (°C)						
rate of change	0.567**	0.359**	1.216**	0.912**	1.731	1.535
maximum	158.286	155.571	178.375	173.500	169.625	171.375
maximum change	72.429	71.000	83.250	79.250	89.750	91.500
Mean Skin Temperature (°C)						
rate of change	0.047**	0.028**	0.075**	0.058**	0.106**	0.081**
maximum	37.700**	37.429**	37.775	37.413	37.900**	37.325**
maximum change	5.200	5.071	5.088	5.050	5.450*	4.850*
Rectal Temperature (°C)						
rate of change	0.015**	0.009**	0.027**	0.022**	0.032	0.029
maximum	38.843	38.986	38.850	38.850	38.837	38.850
maximum change	1.814	1.914	1.825	1.913	1.688	1.800
Tolerance Time (minutes)						
maximum	134.290**	241.430**	70.630**	90.630**	53.130*	63.750*

** Means are significantly different between garment systems (at each intensity of exercise) when subjected to Independent Samples t-tests (p<.05).

* Means are significantly different between garment systems (at each intensity of exercise) exercise) when subjected to Independent Samples t-tests (p<.10).

significant differences in heart rate (rate of change) between garment systems. Significant differences between the garment systems were found for low and moderate levels of exercise for heart rate (rate of change), but not for heavy exercise level (Table 5).

Mean skin temperature. Two-way ANOVA (Table 4) found significant main effects of exercise level and garment system, but no interaction effect for rate of change of mean skin temperature; a significant main effect of garment system on maximum mean skin temperature, but no main effect of exercise level, and no interaction effect. No main effects or interaction effect between exercise level and garment system were present for the maximum change in mean skin temperature. Independent samples t-tests were performed at each exercise level separately to determine significant differences between garment systems (Table 5). Significant differences between the garment systems, for mean skin temperature (rate of change) were found for all three levels of exercise. Significant differences in maximum mean skin temperature between garment systems were observed for low and heavy levels of exercise. Significant differences in maximum change in mean skin temperature were observed for heavy intensity exercise only.

Rectal temperature. Two-way ANOVA (Table 4) found significant main effects of exercise level and garment system on the rate of change for rectal temperature. No interaction effect was present. No main effects or interaction effects between exercise level and garment system were present for either measures of maximum or maximum change in rectal temperature. Independent samples t-tests were performed at each exercise level separately to determine significant differences between garment systems for rectal temperature (rate of change) (Table 5). Significant differences between garment systems were found for low and moderate levels of exercise, but not for heavy exercise level.

Tolerance time. Two-way ANOVA (Table 4) found significant main effects as well as interaction effects of garment system and exercise level for subject tolerance time.

One-way ANOVA with Duncan's multiple range tests was performed to determine differences in tolerance time among exercise levels. Tolerance time during light intensity exercise was significantly higher than that during either moderate or heavy intensity exercise levels which did not differ significantly. Independent samples t-tests were performed at each exercise level separately to determine differences between garment systems for tolerance time, the results of the analyses reflect the interaction effect discovered in the Two-way ANOVA. Independent samples t-tests (Table 5) for low intensity exercise levels found significant differences in tolerance time between garment systems, tolerance time for garment system 4 being almost twice as long as for garment system 3 at low intensity exercise levels. Independent samples t-tests for moderate intensity exercise also found significant differences in tolerance time between garment systems. The tolerance time for garment system 4 was still longer than garment system 3, however the difference was not as large as that for low intensity exercise. Independent samples t-test for heavy intensity exercise found significant differences in tolerance time between garment systems only at the $p<.10$ level.

Effect of Garment System on Physiological Measures (Garment System 2 and 3)

Pearson's correlation analysis was used to determine the strength of the linear associations among the physiological measures (Appendix D). The analysis combined physiological measures of the subjects for both garment systems. Correlation coefficients were found to be both positive and negative and ranged from .005 to -.918. The correlation analyses were used to assess the possibility of combining the physiological measures into a smaller subset or index for ease of statistical analysis. Factor analyses were performed, however, no such subset of variables was obtained. The correlation analyses were also helpful in explaining results of other statistical analyses.

> Ho_3: There are no significant differences in physiological measures from human wear trials between CB protective garment systems 2 and 3.

Null hypothesis 3 was rejected. The means for new variables created from McLellan et. al.'s (1997) study are reported for the two garment systems (Table 6). Independent samples t-tests were performed to determine if there were significant differences between garment systems for each physiological measure. Garment system 2 had a significantly lower rate of change for rectal temperature, maximum mean skin temperature, and tolerance time. There were no significant differences between systems for any of the other physiological variables (Table 6).

Table 6. Mean of New Variables Created from the McLellan et. al. (1997) Study

NEW VARIABLES		GARMENT SYSTEMS	
		2	3
Heart Rate			
rate of change	(max beats/min•minutes^{-1})	0.537	0.734
maximum	(max beats/min)	156.250	159.750
maximum change	(Δ beats/min)	81.000	81.875
Mean Skin Temperature			
rate of change	(max °C•minutes^{-1})	0.034	0.036
maximum	(max °C)	37.376**	37.826**
maximum change	(Δ°C)	4.413	4.336
Rectal Temperature			
rate of change	(max °C•minutes^{-1})	0.013***	0.018***
maximum	(max °C)	38.854	38.939
maximum change	(Δ°C)	1.944	2.052
Tolerance Time			
maximum	(max min)	171.88*	128.130*

***Means are significantly different between garment systems at the $p<.01$ level.
**Means are significantly different between garment systems at the $p<.05$ level.
* Means are significantly different between garment systems at the $p<.10$ level.

Effect of Garment System on Subjective Comfort Measures for Garment Systems 3 and 4

Pearson's correlation analyses (Appendix E) were performed among the three comfort scales and total comfort at both levels of physical effort. For low physical effort, correlation coefficients were found to be positive and ranged from .035 to .924. Correlation coefficients for strenuous physical effort ranged from .360 to .930. Correlation analyses were helpful in explaining results of other statistical analyses.

> Ho$_4$: There are no significant differences in subjective comfort measures from human wear trials among the CB protective garment systems 3 and 4 for each physical effort level.

Null hypothesis 4 was rejected. Table 7 summarizes main effects of garment system and physical effort level and interaction effects found by two-way ANOVA for each dependent variable. Two-way ANOVA (Table 7) found a significant effect of effort level for "very cold vs. very hot" but no main effect of garment system or interaction effect; a significant main effect of effort level and garment system, but no interaction effect for " very comfortable vs. very uncomfortable", " very dry vs. very wet" and "total comfort rating".

Table 7. Summary of Two-way ANOVA: Effect of Garment System and Physical Effort Level on Subjective Comfort Measures (F-Statistic)

	Main Effects		**Interaction Effects**
Dependent variables	Garment system	Effort level	
very cold vs. very hot	0.566	19.713*	0.566
very comfortable vs. very uncomfortable	11.883*	22.096*	0.098
very dry vs. very wet	8.269*	14.818*	0.019
total comfort rating	9.173*	28.982*	0.009

*significance level p<.01

Table 8 summarizes for each effort level, comfort sensation adjective pairs for each garment system. Independent samples t-tests were performed separately at both low and strenuous effort levels to determine differences in garment systems for each comfort measure. For both physical effort levels, significant differences between garment systems were found for all subjective comfort measures except for "very cold vs. very hot".

Table 8. Summary of Comfort Sensation Adjective Pairs

	Garment System	
Adjective pairs	**3**	**4**
Low effort		
very cold vs. very hot	4.8	4.8
very comfortable vs. very uncomfortable	4.60***	3.40***
very dry vs. very wet	4.20**	3.10**
total comfort	13.60**	17.89**
Strenuous effort		
very cold vs. very hot	6.33	5.89
very comfortable vs. very uncomfortable	6.00*	5.00*
very dry vs. very wet	5.56*	4.56*
total comfort	17.89*	15.44*

*** Means are significantly different between garment systems at the p<.01 level.
** Means are significantly different between garment systems at the p<.05 level.
* Means are significantly different between garment systems at the p<.10 level.

Effect of Garment System on Subjective Comfort Measures (Garment Systems 1 and 2)

Ho_5: There are no significant differences in subjective comfort measures from human wear trials among CB protective garment systems 1 and 2.

Null hypothesis 5 was accepted. Table 9 shows, for mid-trial and post-trial questionnaires, mean scores from comfort sensation adjective pairs for each garment system. Two-way ANOVA was performed on mean scores for each adjective pair. No main effects of garment system or questionnaire, and no interactions effects were found for any adjective pair except for a significant main effect of questionnaire on the overall comfort rating.

Correlations Between Textile Properties and Human Physiological Measures for Garment Systems 3 and 4

Ho_6: There are no relationships between physical textile property measures and human physiological measures for garment systems 3 and 4.

Analyses to determine relationships between textile data and physiological measures were performed separately for each exercise level. Previous analyses (see Table 4) determined that for light intensity exercise, the rate of change of all physiological measures, mean skin temperature (maximum) and tolerance time were found to best differentiate between garment systems. For this reason only these variables were used in further analyses of the light intensity exercise data. The variables that best differentiate between garment systems for moderate intensity exercise were rate of change for all physiological measures and tolerance time. The variables that best differentiated garment systems in the heavy intensity exercise group were determined to be mean skin temperature (rate of change, maximum and maximum change) and tolerance time (see Table 4). Therefore these variables were used to further analyse the heavy intensity

Table 9. Mean Score for Each Comfort Sensation Adjective Pair for Each Questionnaire and Garment System

	Mid-trial Questionnaire		Post-trial Questionnaire	
Adjective Pairs	**system 1** (n=14)	**system 2** (n=13)	**system 1** (n=12)	**system 2** (n=11)
Satisfactory vs. Unsatisfactory	5.43	5.15	5.83	6.00
Non-sticky vs. Sticky	3.57	4.38	4.33	4.27
Dry vs. Wet	3.31	3.08	3.92	3.55
Cold vs. Hot	3.08	2.92	3.18	3.00
Acceptable vs. Unacceptable	5.14	5.15	5.83	5.64
Breathable vs. Not Breathable	4.71	4.15	4.83	4.00
Like vs. Dislike	5.00	5.38	5.75	5.73
Appropriate for task vs. Inappropriate	5.07	5.62	5.08	5.64
Appropriate for work environment vs. Inappropriate	4.29	4.85	4.25	5.27
Overall Comfort Rating	5.14	5.46	5.92	6.27

exercise data.

Null hypothesis 6 was rejected. Pearson's correlation analyses were performed separately for each exercise level (Tables 10, 11, 12). Correlations between the human physiological measures and physical textile data were generally higher for light than for moderate exercise levels. The physiological variables used in the correlation analyses for heavy exercise consisted of mean skin temperature and tolerance time only. Correlations for mean skin temperature for heavy exercise were generally higher than for light and moderate exercise, but correlations for tolerance time were lower for heavy exercise.

Light Intensity Exercise. Pearson's correlation analysis (Table 10) found high, positive correlations significant at the p<.01 level between air permeability and tolerance time; each method of water vapour resistance and rectal temperature (rate of change); absorbency and tolerance time; evaporative heat loss and tolerance time; and thermal resistance and rectal temperature (rate of change). High positive correlations significant at the p<.05 level were found between water vapour resistance (CGSB method), thermal resistance and heart rate (rate of change); and thermal resistance and mean skin temperature (rate of change) and (maximum). High negative correlations significant at the p<.01 level were found between air permeability and rectal temperature (rate of change); water vapour resistance (CGSB method) and tolerance time; absorbency and mean skin temperature as well as rectal temperature (rate of change); evaporative heat loss and rectal temperature; and thermal resistance and tolerance time. High negative correlations significant at the p<.05 level were found between air permeability and mean skin temperature (rate of change) as well as mean skin temperature (maximum); absorbency and heart rate (rate of change); and evaporative heat loss and heart rate as well as mean skin temperature (rate of change) and (maximum).

Table 10. Correlations (R) of Physiological Measures and Physical Textile Properties for **Light** Intensity Exercise

	Heart rate (rate of change)	Mean skin temperature (rate of change)	Mean skin temperature (maximum)	Rectal temperature (rate of change)	Tolerance time
Air Permeability	-.463	-.615*	-.591*	-.797**	.737**
Water vapour diffusion resistance (CGSB)	.592*	.486	.503	.910**	-.767**
Water vapour diffusion resistance (VBW)	.248	.145	.267	.684**	-.477
Absorbency	-.597*	-.669**	-.502	-.912**	.805**
Evaporative heat loss	-.615*	-.619*	-.605*	-.816**	.753**
Thermal Resistance	.588*	.636*	.577*	.907**	-.823**

**. Correlation is significant at p<.01.
*. Correlation is significant at p<.05.

Moderate Intensity Exercise. Pearson's correlation analysis (Table 11) found only one negative correlation significant at the p<.01 level between thermal resistance and tolerance time. High positive correlations significant at the p<.05 level were found to exist between thermal resistance and all rate of change physiological measures; water vapour resistance (CGSB method) and heart rate (rate of change); and absorbency and tolerance time. Negative correlations significant at the p<.05 level were found to exist between evaporative heat loss and all physiological measures for rate of change; absorbency and heart rate (rate of change) as well as rectal temperature rate of change; air permeability and heart rate (rate of change); and water vapour resistance and tolerance time.

Table 11. Correlations (R) of Physiological Measures and Physical Textile Properties for **Moderate** Intensity Exercise

	Heart rate (rate of change)	Mean skin temperature (rate of change)	Rectal temperature (rate of change)	Tolerance time
Air Permeability	-.526*	-.430	-.430	.487
Water vapour diffusion resistance (CGSB)	.529*	.476	.507*	-.597*
Water vapour diffusion resistance (VBW)	.509*	.188	.452	-.371
Absorbency	-.599*	-.484	-.596*	.612*
Evaporative heat loss	-.584*	-.527*	-.593*	.549*
Thermal Resistance	.604*	.520*	.573*	-.626**

**. Correlation is significant at p<.01.
*. Correlation is significant at p<.05.

Heavy Intensity Exercise. Pearson's correlation analysis (Table 12) found significant correlations at the p<.01 level between all physical textile properties and the maximum mean skin temperature except for water vapour resistance (CGSB method) which was significant at the p<.05 level. Significant correlations at the p<.01 level were found between air permeability, absorbency, evaporative heat loss and thermal resistance and rate of change for mean skin temperature; water vapour resistance (CGSB method) was significant at the p<.05 level . The only significant correlation at the p<.05 level for maximum change in mean skin temperature was with evaporative heat loss. No significant correlations were found between any of the physical textile properties and tolerance time at high intensity exercise.

Table 12. Correlations (R) of Physiological Measures and Physical Textile Properties for **Heavy** Intensity Exercise

	Mean skin temperature (rate of change)	Mean skin temperature (maximum)	Mean skin temperature (maximum change)	Tolerance time
Air Permeability	-.633**	-.740**	-.435	.475
Water vapour diffusion resistance (CGSB)	.589*	.614*	.308	-.447
Water vapour diffusion resistance (VBW)	.424	.625**	.342	-.299
Absorbency	-.629**	-.728**	-.455	.396
Evaporative heat loss	-.704**	-.818**	-.592*	.384
Thermal Resistance	.685**	.735**	.468	-.462

**. Correlation is significant at p<.01.
*. Correlation is significant at p<.05.

Building the Estimated Physiological Comfort (EPC) Index (Garment Systems 3 and 4)

The objective of building an Estimated Physiological Comfort Index was not achieved. However, regression models were obtained for physiological measures that were able to differentiate between garment systems. Multiple linear regression was used to determine which physical textile properties would best predict human physiological responses while wearing the given CB protective garment systems. To confirm the assumptions necessary for hypothesis testing in regression analysis, the following were obtained: plots of standardized residuals vs. standardized predicted values, histograms of standardized residuals, normal probability (P-P plots), plots of actual vs. predicted values, and collinearity diagnostics. The results of these tests in regards to assumptions of regression analysis will be discussed further in Chapter 5. Appendix F shows an example of typical regression output including all plots for a given physiological variable.

For garment systems 3 and 4, different regression analyses were performed for each exercise level. Table 13 shows the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population for **light** intensity exercise. The adjusted R^2 is an estimate of how well the regression model will fit another data set from the same population.

Table 13. **Light** Intensity Exercise: Coefficients of Determination (R^2) Among Physical Textile Data and Human Physiological Data

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
Heart rate (rate of change)	Evaporative heat loss	.615	.378	.326
	Air permeability	.774	.600	.527
Mean skin temperature (rate of change)	Absorbency	.669	.448	.402
	Water vapour diffusion resistance (CGSB)	.813	.661	.600
Mean skin temperature (maximum)	Evaporative heat loss	.605	.366	.314
Rectal temperature (rate of change)	Absorbency	.912	.833	.819
Tolerance time	Thermal resistance	.823	.677	.650

The first analysis regressed the rate of change in heart rate with all six physical textile properties (air permeability, water vapour diffusion resistance CGSB and VBW method, absorbency, evaporative heat loss and thermal resistance). The coefficient of determination adjusted for the population was .33 for evaporative heat loss, a significant increase in the adjusted R^2 was observed when air permeability was included in the model. No additional variables contributed significantly to a change in the R^2 value and were therefore not included in the model. Consequently, the explained variation in heart rate (rate of change) accounted for by evaporative heat loss and air permeability is 53 percent.

As for the dependent variable of heart rate, mean skin temperature (rate of change) was regressed with all six physical textile properties. The adjusted R^2 was .40 with only the independent variable of absorbency; a significant increase in R^2 was observed when water vapour diffusion resistance (CGSB method) was included in the model. Therefore, sixty percent of the explained variation in mean skin temperature (rate of change) is accounted for by the textile properties of absorbency and water vapour resistance. However only 31% of the explained variation in maximum mean skin temperature can be accounted for by evaporative heat loss.

When rectal temperature and the six textile properties were regressed together, absorbency alone accounted for 82% of the explained variation in rectal temperature (rate of change). Thermal resistance was the textile property that was able to account for 65% of the explained variation in tolerance time. Addition of the other independent variables did not make a significant contribution to R^2, they were therefore not included in the models.

Table 14 shows the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population for **moderate** intensity exercise. The first analysis for moderate intensity exercise group regressed heart rate (rate of change) with all six physical textile properties. The coefficient of determination adjusted for the population was .32 for the property of thermal resistance. No additional variables contributed significantly to an increase in R^2 and therefore they were not included in the model. When rate of change in heart rate was regressed with the six textile properties, it was found that 23 percent of the explained variation in heart rate (rate of change) is accounted for by evaporative heat loss of the fabric system.

Table 14. **Moderate** Intensity Exercise: Coefficients of Determination (R^2) Among Physical Textile Data and Human Physiological Data

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
Heart rate (rate of change)	Thermal resistance	.604	.365	.320
Mean skin temperature (rate of change)	Evaporative heat loss	.527	.277	.226
Rectal temperature (rate of change)	Absorbency	.596	.355	.309
Tolerance time	Thermal resistance	.626	.392	.348

Similar to light intensity exercise, it was found for rectal temperature (rate of change, moderate exercise) that absorbency was the best predictor, however absorbency accounted for only 31% of the explained variation in the rate of change in rectal temperature for moderate intensity exercise. Similar to heart rate (rate of change), the best predictor of tolerance time for moderate intensity exercise was found to be thermal resistance which accounted for 35% of the explained variation in tolerance time.

Table 15 shows the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population for **heavy** intensity exercise. The dependent variables of mean skin temperature (rate of change, maximum, and maximum change) were regressed in separate analyses with all six physical textile properties. For all three independent skin temperature variables, evaporative heat loss was determined to be the best predictor. However, for maximum change in mean skin temperature, evaporative heat loss was found to account for only 31% of the explained variation, and a significant increase in the adjusted R^2 (.57) was observed when water vapour diffusion resistance

(CGSB method) was included in the model. No additional variables contributed significantly to a change in the R^2 value; they were therefore not included in the model. Tolerance time was also regressed with all six independent variables, however the significance level for variable entry to and removal from the model was changed to p=.10 for entry and p=.15 for the removal of variables.

Table 15. **Heavy** Intensity Exercise: Coefficients of Determination (R^2) Among Physical Textile Data and Human Physiological Data

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
Mean skin temperature (rate of change)	Evaporative heat loss	.704	.495	.459
Mean skin temperature (maximum)	Evaporative heat loss	.818	.668	.645
Mean skin temperature (maximum change)	Evaporative heat loss	.592	.351	.305
	Water vapour diffusion resistance (CGSB)	.793	.629	.572
Tolerance time (maximum minutes)	Air Permeability	.475	.226	.171 [1]

Note [1] Stepwise regression analysis with entry criteria set at p=.10 and removal set at p=.15

Correlations Between Textile Properties and Human Physiological Measures (Garment Systems 2 and 3

Ho_7: There are no relationships between physical textile measures and human physiological measures for garment systems 2 and 3.

Previous analyses (see Table 9) determined that maximum mean skin temperature, rate of change in rectal temperature, and tolerance time were found to best differentiate between garment systems. For this reason only these variables were used in further analyses.

Null hypothesis 7 was rejected. Pearson's correlation analysis (Table 16) found one correlation significant at the $p<.01$ level between air permeability and rate of change in rectal temperature. All other correlations between rectal temperature (rate of change) and physical textile properties were significant at the $p<.05$ level except for water vapour resistance (VBW method). High correlations significant at the $p<.05$ level were found to exist between maximum mean skin temperature and air permeability, water vapour resistance (CGSB method), absorbency, and thermal resistance. No significant correlations were found between tolerance time and any of the physical textile properties.

Table 16. Correlations (R) of Physiological Measures and Physical Textile Properties (1997 Study) Garment Systems 2 and 3

	Mean skin temperature (maximum)	Rectal temperature (rate of change)	Tolerance time
Air Permeability	-.505*	-.626**	.482
Water vapour diffusion resistance (CGSB)	.557*	.553*	-.401
Water vapour diffusion resistance (VBW)	.459	.489	-.297
Absorbency	-.543*	-.614*	.450
Evaporative heat loss	-.470	-.592*	.459
Thermal Resistance	.545*	.615*	-.449

**. Correlation is significant at $p<.01$.

*. Correlation is significant at $p<.05$.

Building the Estimated Physiological Comfort (EPC) Index (garment systems 2 and 3)

The development of a Physiological Comfort Index was not achieved. However, regression models were obtained for each physiological measure that was able to differentiate between garment systems. Multiple linear regression was used to determine which physical textile properties would best predict human physiological responses while wearing CB protective garment systems 2 and 3. Table 17 shows the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population. The first analysis regressed maximum mean skin temperature with all six physical textile properties (air permeability, water vapour diffusion resistance CGSB and VBW method, absorbency, evaporative heat loss and thermal resistance). Water vapour diffusion resistance was confirmed to account for 26% of the explained variation in maximum mean skin temperature measure. The second analysis regressed rate of change in rectal temperature with all six physical textile properties. Air permeability was found to account for 35 % of the explained variation in rectal temperature (rate of change). No additional textile properties were found to contribute significantly to an increase in R^2; they were therefore not included in either model. Tolerance time was also regressed with all six independent variables, however the significance level for variable entry to and removal from the model was changed to p=.10 for entry and p=.15 for the removal of variables. From this regression it was determined that air permeability was able to account for 18% of the explained variation in tolerance time.

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Table 17. Coefficients of Determination (R^2) Among Physical Textile Data and Human Physiological Data (Garment Systems 2 and 3)

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
Mean skin temperature (maximum)	Water vapour diffusion resistance (CGSB)	.557	.311	.261
Rectal temperature (rate of change)	Air permeability	.626	.391	.348
Tolerance time (maximum minutes)	Air permeability	.482	.232	.177 [1]

Note [1] Stepwise regression analysis with entry criteria set at p=.10 and removal set at p=.15

Correlations Between Textile Properties and Subjective Comfort Measures for Garment Systems 3 and 4

Ho_8: There are no relationships between physical textile property measures and human subjective comfort measures for garment systems 3 and 4.

Null hypothesis 8 was rejected. Pearson's correlation analyses were performed separately for each physical effort level (Tables 18 and 19). Correlations between subjective comfort measures and the physical textile data were all greater for low than for strenuous physical effort levels.

Low Physical Effort. Pearson's correlation analysis found no significant correlations with any of the textile properties and "very cold vs. very hot". High significant correlations were found for all physical textile properties except resistance to water vapour diffusion (VBW method) and "very comfortable vs. very uncomfortable" (Table 18). Significant correlations were found to exist between all of the physical textile properties (except for both methods of resistance to water vapour diffusion) and "very dry vs. very wet". Significant correlations were found to exist between all of the physical textile properties and the total comfort rating except for the VBW method for water vapour resistance.

Table 18. Correlations (R) of Subjective Comfort Measures and Physical Textile Properties for **Low** Physical Effort (Garment Systems 3 and 4)

	Very comfortable vs. Very uncomfortable	Very dry vs. Very wet	Total comfort
Air Permeability	-.692**	-.458*	-.582**
Water vapour diffusion resistance (CGSB)	.576**	.408	.458*
Water vapour diffusion resistance (VBW)	.313	.360	.223
Absorbency	-.609**	-.478*	-.507*
Evaporative heat loss	-.636**	-.480*	-.517*
Thermal Resistance	.641**	.491*	.528*

**. Correlation is significant at p<.01.
*. Correlation is significant at p<.05.

Strenuous Physical Effort. Similar to the low effort level, Pearson's correlation analysis found no significant correlations with any of the textile properties and "very cold vs. very hot". Significant correlations were found between air permeability, evaporative heat loss, thermal resistance and "very comfortable vs. very uncomfortable". Only one significant correlation was found between the textile properties and "very dry vs. very wet" with thermal resistance. Significant correlations were found to exist between air permeability, thermal resistance and the total comfort rating.

Table 19. Correlations (R) of Subjective Comfort Measures and Physical Textile Properties for **Strenuous** Physical Effort (Garment Systems 3 and 4)

	Very comfortable vs. Very uncomfortable	Very dry vs. Very wet	Total comfort
Air Permeability	-.544**	-.356	-.481**
Water vapour diffusion resistance (CGSB)	.359	.382	.375
Water vapour diffusion resistance (VBW)	.079	.229	.108
Absorbency	-.375	-.367	-.377
Evaporative heat loss	-.404*	-.379	-.387
Thermal Resistance	.427*	.428*	.436*

**. Correlation is significant at p<.05.
*. Correlation is significant at p<.10.

Building the Estimated Subjective Comfort (ESC) Index (Data from Systems 3 and 4 Only)

As for the physiological studies, the development of a Estimated Subjective Comfort Index was not achieved. However, regression models were obtained for each subjective comfort measure that was able to differentiate between garment systems. Multiple linear regression was used to determine which physical textile properties would best predict subjective comfort responses while wearing CB protective garment systems 3 and 4. To confirm the assumptions necessary for hypothesis testing in regression analysis, the following were obtained: plots of standardized residuals vs. standardized predicted values, histograms of standardized residuals, normal probability (P-P plots), plots of actual vs. predicted values, and collinearity diagnostics. The results of these tests in regards to the assumptions of regression analysis will be further discussed in Chapter 5. Appendix G shows an example of typical regression output including all plots for a given subjective comfort variable.

For garment systems 3 and 4, different regression analyses were performed for each physical effort level. Table 20 shows for **low** physical effort the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population. The first analysis regressed "very comfortable vs. very uncomfortable" with all six physical textile properties (air permeability, water vapour diffusion resistance CGSB and VBW method, absorbency, evaporative heat loss and thermal resistance). Air permeability was confirmed to account for 45% of the explained variation in the subjective measure of "very comfortable vs. very uncomfortable". No additional variables contributed significantly to an increase in R^2; they were therefore not included in the model.

Table 20. Coefficients of Determination (R^2) Among Physical Textile Data and Subjective Comfort Data for **Low** Effort (Garment Systems 3 and 4)

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
very comfortable vs. very uncomfortable	air permeability	.692	.479	.450
very dry vs. very wet	thermal resistance	.491	.241	.199
total comfort	air permeability	.582	.339	.302

As for the last dependent variable, "very dry vs. very wet" for low physical effort was regressed with all six physical textile properties. The adjusted R^2 was .20 with the independent variable of thermal resistance. Therefore, the explained variation in the sensation of dry versus wet accounted for by thermal resistance was 20%. When the total comfort rating and the six textile properties were regressed together air permeability alone accounted for 30% of the explained variation in the total comfort rating. The addition of other independent variables were not found to make a significant contribution to an increase in R^2 and consequently were not included in either predictive model.

Table 21 shows the coefficients of correlation (R), coefficients of determination (R^2) and R^2 adjusted for the population for **strenuous** physical effort. The first analysis regressed "very comfortable vs. very uncomfortable" with all six physical textile properties. The coefficient of determination adjusted for the population was .25 for the property of air permeability. Additional variables did not contribute to a significant increase in R^2; they were therefore not included in the model. As for the low physical effort group, air permeability was also found to be the main predictor of the total comfort rating, however the coefficient of determination was much lower (adjusted R^2 = .18).

Due to the fact that only one of the correlation coefficients for "very dry vs. very wet" was significant at the $p<.10$ level, the significance level for variable entry to and removal from the regression model was changed to $p=.10$ for entry and $p=.15$ for the removal of variables. When "very dry vs. very wet" was regressed with all six textile properties, it was found that 13 percent of the explained variation in the sensation of dry versus wet was accounted for by thermal resistance of the fabric system.

Table 21. Coefficients of Determination (R^2) Among Physical Textile Data and Subjective Comfort Data for **Strenuous** Effort (Garment Systems 3 and 4)

REGRESSION DEPENDENT VARIABLES	INDEPENDENT VARIABLES IN THE MODEL	R	(R^2)	ADJUSTED (R^2)
very comfortable vs. very uncomfortable	air permeability	.544	.296	.252
very dry vs. very wet	thermal resistance	.428	.183	.132[1]
total comfort	air permeability	.481	.231	.183

Note[1] Stepwise regression analysis with entry criteria set at $p=.10$ and removal set at $p=.15$

Correlations Between Textile Properties and Subjective Comfort Measures (Garment Systems 1 and 2

Ho$_9$: There are no relationships between physical textile property measures and human subjective comfort measures for garment systems 1 and 2.

Null hypothesis 9 was not tested. Due to the fact that there were no significant differences in subjective comfort ratings between garment systems, no further analyses were conducted using this data set.

Chapter 5

DISCUSSION

The purpose of this research was to determine which physical textile properties, alone or in combination, would best predict human physiological and subjective comfort while wearing CB protective clothing ensembles. Small scale laboratory tests were conducted on each multi-layer fabric system to measure the following textile properties: dry heat transfer, evaporative heat loss, water vapour diffusion resistance, liquid absorbency and air permeability. Data collected from the fabric systems were then correlated with secondary human wear trial data to determine relationships between physical textile properties, physiological and subjective measures.

Objective 1: Physical Textile Properties

The first objective of this study was to measure various forms of *dry and evaporative heat transfer*, *moisture transfer* and *air permeability* through textile materials commonly used in chemical/biological defence suits and to determine differences in these measures among fabric systems. This objective was achieved. Four different CB protective fabric systems were measured for the following properties: dry heat transfer, evaporative heat loss, water vapour diffusion resistance, liquid absorbency and air permeability.

One-way ANOVA found that for pairs of fabric systems used in each human wear trial (systems 2 and 3; systems 3 and 4), physical textile properties in each fabric system pair were significantly different except for thermal conductivity and water vapour diffusion resistance using the VBW method. Overall CGSB method 49 gave higher values of water vapour diffusion resistance. VBW resistance measures were lower which may be due to the experimental equipment set up. Fabric specimens in the VBW apparatus were positioned closer to the water chamber, this would produce different values for water vapour resistance than the CGSB method which uses a different apparatus.

Fabric system 4 was more air permeable, had a lower resistance to water vapour diffusion (CGSB method) and dry heat transfer and a higher absorbency rate than system 3. Absorbency was greater for system 4 than system 3 due to the white polyester inner layer being able to easily wick moisture along the surface of the fabric. Water tended to bead on the tightly knit, hydrophobic surface of system 3. Even though fabric system 4 was composed of three fabric layers it was still more air permeable than system 3 which had only two layers, but was almost four and a half times thicker than system 3. Another factor affecting air permeability was the complex foam pathway air must pass through as opposed to the simpler knit layers in system 4.

As the measures of air permeability, water vapour diffusion and thermal resistance are highly related to one another, similar reasons may be used to explain why system 4 allowed greater heat and water vapour to pass through it than system 3. Evaporative heat loss of system 4 was significantly higher than system 3. When the sweating period had stopped, heat loss from system 4 fell rapidly and returned to its original dry heat loss value within an average of 924 seconds. Maximum heat loss and a rapid return to pre-sweating heat loss is desirable as the body is overheated during the periods of sweating. Once sweating has stopped the body is no longer overheated and heat loss should be reduced (Farnworth, 1986).

Fabric system 2 was found to have greater air permeability, higher evaporative heat loss, higher absorbency, and lower resistance to water vapour diffusion and thermal resistance than garment system 3. Basic textile properties used to explain differences between fabric systems 3 and 4 also apply to differences between systems 2 and 3. System 2 was more air permeable, and allowed a greater amount of water and heat to pass through it than system 3 due to the fact that system 2 was composed of a more open knit, laminated with carbon spheres as opposed to the thick foam structure of system 3. The open structure of system 2 may also explain why system 2 had a higher absorbency rate than system 3. Water was able to easily wet the surface of system 2 and absorb into the spaces of the knit and between the carbon spheres.

The results suggest that thermal resistance is lowered by reducing fabric thickness.

System 3 had the highest fabric thickness, and therefore would also have the highest thermal resistance. The number of air layers within a fabric system will also affect thermal resistance. This is evident with system 4 which had three separate layers as opposed to two in the other systems tested. This system had a higher thermal resistance than systems 1 and 2 which only had two fabric layers, but the thermal resistance of system 4 was not as high as system 3 which was four and a half times as thick. Based on physical textile results, it would be expected that fabric system 3 be the least comfortable in terms of physiological and subjective comfort.

Objective 2: Differences in Comfort Measures

The second objective was to determine differences in comfort related measures between garment systems when worn:

a) differences in physiological measures between garment systems 3 and 4,
b) differences in physiological measures between garment systems 2 and 3,
c) differences in subjective comfort measures between garment systems 3 and 4,
d) differences in subjective comfort measures between garment systems 1 and 2.

Objective 2 a: Differences in Physiological Measures

Objective 2 a was to determine differences in physiological measures between garment systems 3 (carbon foam) and 4 (carbon Lycra®). Two-way ANOVA found that heart rate (rate of change) differed significantly for each garment system and exercise level. The other analyses found that both maximum heart rate and maximum change in heart rate were significantly different for each exercise level, but not for the garment system worn. Thus, according to this study, one can say that measures of maximum heart rate and maximum change in heart rate are not able to distinguish between garment systems. One possible explanation for this is that these measures are more affected by the intensity of exercise and the participants' fitness level.

Similar to the measure of heart rate, rate of change in mean skin temperature differed significantly for each garment system and exercise level. Measures of maximum mean skin temperature were able to differentiate between garment systems, but not exercise levels, indicating that the maximum skin temperature attained during the trial was affected by the garment system worn, but not by the exercise level. Two-way ANOVA indicated that measures of maximum change in mean skin temperature were not able to differentiate between either garment system or exercise level.

The rate of change in rectal temperature was determined to best differentiate between garment systems and exercise level. The other measures of rectal temperature (maximum and maximum change) were not able to differentiate between garment system or exercise level. Two-way ANOVA found that garment systems differed significantly for tolerance time, but those differences were affected by the exercise level.

Independent sample t-tests of physiological measures for light and moderate intensity exercise indicated that the rate of change in heart rate, mean skin temperature, rectal temperature, and tolerance time were significantly different for both garment systems. There tended to be a lower rate of change in heart rate, mean skin temperature and rectal temperature when wearing garment system 4. Tolerance times for light, moderate, and heavy exercise groups also tended to favour garment system 4 which allowed for consistently higher tolerance times than system 3. These differences may be attributed to differences in physical textile properties between garment systems. Garment system 4 was more air permeable, had a lower resistance to water vapour diffusion (CGSB method) and dry heat transfer, evaporative heat loss and absorbency rate are also significantly higher than for garment system 3.

For heavy intensity exercise, differences in physiological measures between garment systems were found only for mean skin temperature (rate of change, maximum, and maximum change). Differences in skin temperature between garment systems during heavy exercise demonstrates that garments either did (system 4) or did not (system 3) allow for adequate evaporative heat loss or air permeability to cool the skin surface.

Fabric system 4 had a higher air permeability and a lower resistance to water vapour diffusion than fabric system 3. The lack of differences in measures of heart rate and rectal temperature between garment systems during heavy intensity exercise is an indication that subjects were pushed to extreme levels of heat strain. Differences between garment systems were thus masked by the effects of the intense exercise. Barker and Scruggs' (1996) also found that environmental conditions and work loads have an overwhelming impact on comfort perceptions. They found that no fabric material itself could alleviate discomfort while performing heavy work in hot and humid environments.

Objective 2 b: Differences in Physiological Measures

Objective 2 b was to determine differences in physiological measures between garment systems 2 (carbon spheres) and 3 (carbon foam). Independent samples t-tests found significant differences between garment systems for measures of maximum skin temperature, rectal temperature (rate of change) and tolerance time.

Measures of heart rate did not differ significantly between the garment systems. The level of activity performed during the trial was not high enough to show great differences in work load of the subjects while wearing the garment systems. The maximum mean skin temperature was found to differ depending on which CB protective suit was worn. It was found that subjects were able to participate in the trial for a longer period of time while wearing garment system 2. Also, subjects tended to attain a higher skin temperature while wearing garment system 3. Likewise, rate of change in rectal temperature was higher when wearing garment system 3. These differences in tolerance time and some physiological measures may be attributed to differences in physical textile properties between two garment systems. Garment system 2 was found to have greater air permeability, higher evaporative heat loss, higher absorbency, and a lower resistance to water vapour diffusion and dry heat loss than garment system 3.

Objective 2 c: Differences in Subjective Comfort Measures

Objective 2 c was to determine differences in subjective comfort measures between garment systems 3 (carbon foam) and 4 (carbon Lycra®). In general, results from the Air Force trial (a comparative format trial) indicated the prototype undergarment system was evaluated more favourably than the current CB ensemble. Two-way ANOVA found that the sensation of "very cold vs. very hot" differed significantly between physical effort levels, but not between garment systems worn. Thus, subjects in either garment system felt cooler during low than during strenuous physical activity. The sensations of "very comfortable vs. very uncomfortable", "very dry vs. very wet" and the total comfort differed significantly for each garment system and physical effort level.

Independent sample t-tests of subjective comfort measures for strenuous physical effort indicated that sensations of "very comfortable vs. very uncomfortable", "very dry vs. very wet" and the total comfort differed but these differences were not as significant as the differences for low physical effort ($p<.10$). In both cases, garment system 4 was significantly more comfortable than garment system 3 except for the sensation of cold versus hot which did not differ between systems. Similar to the heavy intensity exercise, in the physiological study for garment system 3 and 4, the differences between the garment systems were reduced by the effects of the strenuous physical activity.

Thus similar trends in differences between garment systems 3 and 4 were found for both subjective comfort and physiological measures. Garment system 4 was rated more favourably for subjective comfort and produced less physiological strain than system 3.

Objective 2 d: Differences in Subjective Comfort Measures

Objective 2 d was to determine differences in subjective comfort measures between garment systems 1 (carbon fibre) and 2 (carbon spheres). Two-way ANOVA found no significant differences in subjective comfort measures between garment systems on either questionnaire except for the overall comfort rating. The overall comfort rating was higher in the post-trial questionnaire, however, both garment systems were perceived by the subjects to be of equal comfort. This may be explained by the following: first, the subjects may have felt more comfortable in both suits at the end of the trial by becoming accustomed to wearing the CB garment systems. Secondly, fabric systems 1 and 2 did not differ in their properties of evaporative heat loss, thermal resistance or resistance to water vapour diffusion. In their work, Markee, et. al. (1990) also found that the lack of statistically significant differences in heat and moisture transport properties predicted that fabrics would be judged as providing similar sensations of thermo-physiological comfort.

Objective 3: Relationships Between Textile Properties and Comfort Measures

To determine relationships between various measures and indices of dry heat transfer, evaporative heat transfer, moisture vapour transfer, moisture absorption, and air permeability of textile materials and measurements taken during human wear trials of clothing constructed of those CB materials:

a) relationships with physiological measures, and

b) relationships with subjective comfort measures.

Checking the Assumptions of Regression Analysis for This Study

Multiple regression as an interpretive tool is used to evaluate the relative importance of independent variables in explaining variation in a dependent variable. There are four main assumptions to be met in a regression analysis: the sample is drawn at random, the sample must have a normal distribution, there must be a linear relationship between the dependent and independent variables, and equal variance must exist between the dependent variables and the independent variables. Multicollinearity within the independent variables is another important topic that will be discussed in the following section.

The sample is drawn at random. The sample size for all of the studies used in this research was relatively small. This is typical of physiological and subjective studies involving the evaluation of garment systems by human subjects. However, the random allocation of data as described on page 53 was used for all correlation and regression analyses. It was necessary to randomly allocate one independent measure to each dependent measure for two reasons. First, the number of cases for the independent and dependent variables were not the same. Second, the fabric systems studied in part one of this study were not sampled from the actual garment systems used in the human wear trials. It was not possible to sample from these garments as they were not available for testing. These limitations of the data are common to most textile experimental research and are not considered to adversely affect the data analysis.

The sample has a normal distribution. Histograms of the standardized residuals were obtained to test the assumption of normality. (Residuals are defined as the error in prediction. More specifically they are the difference between the actual and the estimated value of the dependent variable for each case.) Most of the residuals plotted for each regression analysis did not show a perfectly normal distribution. This is due to the small sample size and the fact that only two garment systems were present in each analysis. P-P plots of normal probability of standardized residuals were also plotted to test for normality. The plots from most of the analyses for the physiological data fall more or less on a straight line, indicating the samples have a close to normal distribution. The plots from the subjective comfort analyses fall further away from the straight line than for the physiological analyses. However, perfectly normal sample distributions would not be possible due to the especially small sample sizes.

There is a linear relationship between the dependent and independent variables. Plots of the dependent variables and the standardized predicted values were used to test the assumption of linearity. All plots show a linear trend, however some of the data points are clustered into two groups along the line. This is again due to the nature of the data; the small sample size and having only two garment systems to compare for all the analyses. Such weaknesses in the data need to be considered when reviewing the results of the regression analyses.

Equal variance exists between the dependent variables and the independent variables. Equal variance can be checked with an examination of residuals by searching for visible patterns in the scatter plots. A lack of pattern in the data points indicates relative freedom from abnormalities. Most of the residuals plotted from the regression analyses appear to be randomly scattered around the horizontal line through zero on the scatter plots.

Multicollinearity. In this study, some of the physical textile properties are highly intercorrelated. The more strongly correlated the independent variables are, the less the reliability of the relative importance indicated by the partial regression coefficient. In a regression analysis, the partial correlation indicates the degree to which a variable accounts for the remaining variation, unaccounted for by the other independent variables. In the majority of the regression models, obtained from the human wear trial data and the physical textile property data, one independent variable was found to best predict the dependent variables. This is due to the fact that the independent variables which are highly correlated to the dependent variable are also highly intercorrelated with the other independent variables, thus they would not be included in the regression model. Collinearity diagnostics were performed to test for multicollinearity between the independent variables. The tolerance statistic was used to measure the strength of the linear relationship among the independent variables. A tolerance value of 1 indicates that the variability of the independent variable is not explained by the other independent variables. A value close to 0 is an indication that an independent variable is highly correlated to the other independent variables and is therefore multicollinear (Norusis, 1997). A variable will not be entered into a regression model if it results in a very small tolerance. As a result, for independent variables that are highly correlated it will not be possible to estimate a regression model that contains all of these variables. Such is the case with most of the regression analyses presented in this study.

Objective 3 a: Relationships Between Textile Properties and Physiological Measures

This objective was to determine relationships between various indices of dry heat transfer, evaporative heat transfer, moisture vapour transfer, moisture absorption, and air permeability and physiological measures. The development of a Physiological Comfort Index was not achieved, however, regression models were obtained for the physiological measures that were able to best differentiate between garment systems. Pearson's correlation analyses were used to determine relationships for each level of exercise. Multiple linear regression was used to develop an index that would best estimate the physiological comfort of the CB protective clothing ensembles.

Building A Regression Model for Physiological Measures (Garment Systems 3 and 4)

Table 22 summarizes the regression models for the physiological measures for all exercise levels. Correlation analyses for light intensity exercise indicated that most textile properties were significantly correlated with the physiological measures. From multiple linear regression analysis it was determined, for **light** intensity exercise, that heart rate (rate of change) was best predicted by a regression model with evaporative heat transfer and air permeability as predicting variables (Table 22). In simpler Pearson's correlations, as evaporative heat loss was found to have the highest significant correlation with heart rate (rate of change), it is logical that this property was found to account for 33 % of the variation in heart rate. Air permeability was included along with evaporative heat loss because it was found to make a significant additional contribution to the predictive model. However, with this being said, air permeability was not found by Pearson's correlation analysis to have a significant correlation with the rate of change in heart rate (R = -.463). One possible explanation for including this variable in the model is that air permeability was found to be highly intercorrelated with the other remaining independent variables. The other textile properties are not included in the model due to the fact that air permeability accounts for the influence of the other variables on the

Table 22. Summary of Regression Models for Physiological Measures for All Exercise Levels (Garment Systems 3 and 4)

		Adjusted R^2		
Physiological Variables	**Predictor Variables**	**Light Intensity**	**Moderate Intensity**	**Heavy Intensity**
Heart rate (rate of change)	Evaporative heat loss & Air permeability	.53	-	N/A
	Thermal resistance	-	.32	
Mean skin temperature (rate of change)	Absorbency & Water vapour (CGSB)	.60	-	-
	Evaporative heat loss	-	.23	.46
Mean skin temperature (maximum)	Evaporative heat loss	.31	N/A	.65
Mean skin temperature (maximum change)	Evaporative heat loss & Water vapour (CGSB)	N/A	N/A	.57
Rectal temperature (rate of change)	Absorbency	.82	.31	N/A
Tolerance time	Thermal resistance	.65	.35	-
	Air permeability	-	-	.18

dependent variable of heart rate (rate of change). Evaporative heat loss was also found to best predict maximum mean skin temperature. However, the rate of change in mean skin temperature was best predicted by absorbency and resistance to water vapour diffusion (CGSB method).

Regression models for **moderate** intensity exercise are similar to light exercise models for rectal temperature and tolerance time (Table 22). Both absorbency and thermal resistance were included in separate models to predict rate of change in rectal temperature and tolerance time respectively. However, the R^2 for moderate exercise tended to be smaller than the R^2 for light exercise. This indicates that models for light intensity exercise were able to explain a higher percentage of the variation in the dependent measures. For heart rate (rate of change), moderate exercise, the regression model included only thermal resistance. It was found for mean skin temperature (rate of change) for moderate exercise that evaporative heat loss made the most significant contribution to the predictive model.

The physiological measures that were determined to best differentiate between garment systems for **heavy** intensity exercise included all three measures of mean skin temperature and tolerance time. Correlation and multiple linear regression analyses (Table 22) confirmed that predicting differences between garment systems is difficult when differences in physiological measures are not significant.

Tolerance time and mean skin temperature were determined to best differentiate between garment systems for heavy intensity exercise. Differences in measures of heart rate and rectal temperature between garment systems were masked by the intense level of exercise. Subjects were brought to extreme levels of heat strain during the experiment which had a greater effect on the subjects than the garment system worn. However, mean skin temperature was found to differ significantly between the garment systems during heavy exercise which indicates that subjects were able to feel cooler in one system than the other.

As for maximum mean skin temperature for light exercise and rate of change in mean skin temperature for moderate exercise, measures of mean skin temperature (rate of change, maximum, and maximum change) for heavy exercise all had the independent variable of evaporative heat loss included in regression models. The measure of mean skin temperature which is more a measure of physical comfort than an indication of heat strain was best predicted by the most complex physical textile measure. This is due to the fact that during heavy intensity exercise the property of evaporative heat loss will have the greatest effect on skin temperature rather than on heart rate and rectal temperature.

Building A Regression Model for Physiological Measures (Garment Systems 2 and 3)

Correlation analyses of the 1997 data set indicated that most textile properties were significantly correlated with physiological measure of rectal temperature (rate of change), maximum mean skin temperature and tolerance time. Low correlations are related to low significant differences in physiological measures between garment systems.

Multiple regression analyses were used to determine which physical textile properties would best predict the physiological measures. A regression model for maximum mean skin temperature included the variable of resistance to water vapour diffusion (CGSB method). Rectal temperature (rate of change) was another dependent variable that was found to differentiate between garment systems 2 and 3. The predictive models for rectal temperature and tolerance time both included the property of air permeability. However, the R^2 was low in the tolerance time model due to the fact that differences between garment systems were not as significant as the differences for the other physiological measures.

Comparison of Models Built from the 1994 Data Set (garment system 3 and 4) and the 1997 Data Set (Garment System 2 and 3)

For the validation of a predictive regression model, the variables in the model for identical physiological measures should not change over time, with different subjects or garment systems. In the 1994 McLellan et. al. study, subjects in the light intensity exercise group performed similar light exercise in the same environmental conditions as subjects in the 1997 McLellan et. al study. It is therefore possible to compare the models from both studies to ensure the same predictive variables were determined for identical physiological measures.

Similar models were not found for the corresponding physiological measures from both studies, in addition the coefficients of determination tended to be lower for the 1997 study. There are several reasons for the differences in predictive models from study to study. First of all, the pairs of garment systems evaluated in the studies were different. These differences may have been large enough to cause the subjects to experience distinct physiological responses which would affect the outcome of the regression analysis. Secondly, different subjects were used in each study. One group of participants may have had a higher level of fitness than the other and therefore may not have been affected as much by the garment system worn. Also, although both groups participated in light exercise, the duration of exercise and rest periods were different.

By comparing the regression models obtained from the three exercise levels, it is evident that the intensity of exercise does play a role in which physiological measures will best differentiate the garment systems from one another and in turn which independent variables will best predict physiological performance. It may be stated that for mean skin temperature for all exercise levels the best predicting variable was evaporative heat loss with the exception of rate of change in skin temperature of light exercise.

Regression models obtained from each exercise level were compared to determine why various regression models were similar or different among the different physiological measures. For light intensity exercise, correlation coefficients (see Appendix E) are low between the measures of: rate of change in heart rate and mean skin temperature (rate of change); mean skin temperature rate of change and maximum; mean skin temperature (maximum) and rectal temperature (rate of change); and mean skin temperature (maximum) and tolerance time. Therefore it would not be expected that these measures have the same independent variables present in the regression models which is the case in this study. However, for measures that are highly correlated: rectal temperature (rate of change) and tolerance time; tolerance time, heart rate (rate of change) and mean skin temperature (rate of change); rectal temperature (rate of change), heart rate (rate of change) and mean skin temperature (rate of change), it would be expected that these physiological measures have the same predictive variables in the regression models which is not the case from the results of this study.

Similar predictive variables should also be found for highly correlated physiological measures taken during moderate intensity exercise (tolerance time and all three physiological measures; and heart rate (rate of change and rectal temperature (rate of change). However this is not the case except for tolerance time and heart rate (rate of change) which both have thermal resistance as a predictive variable in the regression model and similar R^2 values. For heavy exercise only two groups of physiological measures are highly correlated: tolerance time and mean skin temperature (rate of change, maximum and maximum change). The last two pairs of physiological measures have evaporative heat loss as the main predictive variable. However, for tolerance time and mean skin temperature similar regression models were not obtained.

Objective 3 b: Relationships Between Textile Properties and Subjective Comfort

To determine relationships between various indices of dry heat transfer, evaporative heat transfer, moisture vapour transfer, moisture absorption, and air permeability of textile materials and subjective comfort measures. Similar to the other studies, the development of a Estimated Subjective Comfort Index was not achieved, however, regression models were obtained for each subjective comfort measure that was able to differentiate between garment systems.

Building A Regression Model for Subjective Comfort Measures (Garment Systems 3 and 4)

In general, the correlation coefficients were lower for strenuous than for low physical effort. This is similar to the physiological data which indicated the correlation coefficients were lower for heavy than for light intensity exercise. Correlation analyses for low and strenuous physical effort indicated no significant correlations between any of the physical textile properties and comfort sensations of cold versus hot. For **low** physical effort, high significant correlations were found for most physical textile properties and "very comfortable vs. very uncomfortable", "very dry vs. very wet"and the total comfort rating.

For **strenuous** exercise, significant correlations were found between "very comfortable vs. very uncomfortable" and the textile properties except for both methods of water vapour diffusion resistance and absorbency. Only one moderately significant correlation was found between thermal resistance and "very dry vs. very wet". Thermal resistance and air permeability were the only properties moderately correlated with the total comfort rating. These low correlations reflect the less significant differences in comfort measures for strenuous physical effort levels.

Through multiple linear regression analyses it was determined for both low and strenuous (Table 23) effort levels that the same textile properties were able to predict each subjective comfort sensation. However, coefficients of determination for similar predictive models were lower for strenuous than for low effort levels. This indicates that low effort models were able to explain a higher percentage of the variation in the dependent variables. The differences between garment systems are less significant for strenuous effort levels therefore this group would be expected to have predictive models with lower R^2 values.

For both low and strenuous physical effort, the sensation of comfortable versus uncomfortable was best predicted by a regression model containing the property of air permeability. Thermal resistance was included in both models for low and strenuous effort levels to predict the sensation of dry versus wet. Thermal resistance was able to account for 20% of the explained variation for low effort level, and only 13% of the variation of the dry/wet sensation for strenuous physical effort. Similar to the comfortable/uncomfortable sensation, air permeability found best predict the total comfort rating for both physical effort levels. The R^2 was low for strenuous effort models

Table 23. Summary of Regression Models for Subjective Measures for Each Physical Effort Level (Garment Systems 3 and 4)

		Adjusted R^2	
Subjective Variables	**Predictor Variables**	**Low Effort**	**Strenuous Effort**
"very comfortable vs. very uncomfortable"	Air permeability	.45	.25
"very dry vs. very wet"	Thermal resistance	.20	.13
total comfort rating	Air permeability	.30	.18

due to the fact that the correlations were only moderately high and significant at the $p<.10$ level. This reflects the difficulty in predicting differences when the distinction between garment systems is small.

From regression models obtained from the subjective comfort data it is apparent that physical effort level influences the degree of predictive power held by the regression model. However, physical effort level does not influence the comfort sensations that best differentiate garment systems or textile properties which best predict these measures. Hassenboehler, Nigg and DeJonge (1988) also compared textile properties with subjective field trial results and found that the effect of heat, moisture and air transport provided a good indication of actual thermal comfort, however, no predictive models were developed in their study.

Comparison of Models Built from the Physiological and Subjective Comfort Data

In general, coefficients of determination (adjusted R^2) were lower for the subjective comfort predictive models than for physiological predictive models. However, physiological and subjective regression models showed the same trends with increasing levels of physical exercise. In both cases, coefficients of determination (adjusted R^2) were lower for the group with the higher intensity exercise or effort level. Predictive models for physiological measures showed more diversity in the textile properties present in the regression models among the three exercise levels. Most of the physical textile properties, except for water vapour diffusion resistance (VBW method), were determined to account for some variation in at least some of the physiological measures, whereas, air permeability and thermal resistance were the only independent variables accounting for the variation in subjective comfort measures for both low and strenuous effort.

Building an index of predictive variables was not possible using the regression models obtained from the analyses. This was due to the nature of the data which consisted of highly correlated dependent variables as well as highly intercorrelated independent variables which proved to be a complication with multicollinearity. However, from both physiological and subjective regression models it is evident that a predictive comfort model should include textile properties as well as activity or exercise parameters and environmental conditions. Even an early model of human thermal balance by Martin and Goldman (1972) included such variables as wearer workload, ambient temperature, vapour pressure, air movement and solar load in addition to insulation and evaporative heat transfer properties of fabric systems. Also, as Gibson (1993) points out, lab measures of heat and moisture vapour transfer of textiles are convenient for comparing different fabrics, but they do not take into account factors related to garment fit and design. These lab measures are based on measurements at steady state conditions, however, humans rarely work at a sustained level of work, therefore, steady state measures of the total heat energy and mass transfer through clothing are often inaccurate as they are often not applicable to real life situations.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

Summary

The purpose of this study was to investigate the relationship of physical textile properties of CB protective fabric systems to physiological and subjective responses of individuals wearing the CB garments. Four fabric systems all with the same outer-layer fabric were studied. Small scale laboratory tests were conducted on each multilayer fabric system to measure the following textile properties: dry heat transfer, evaporative heat loss, water vapour diffusion resistance, liquid absorbency and air permeability. Data collected from the fabric systems were correlated with secondary human wear trial data to determine which physical textile properties would best predict human physiological and subjective comfort while wearing CB protective clothing ensembles. Differences in physiological and subjective measures between garment systems were mainly found at lower exercise levels. Overall, differences in textile properties would predict these differences in physiological and subjective measures. However, predictive comfort indices were not developed due to the highly intercorrelated nature of the independent variables.

Conclusions

The conclusions based on this study are as follows:

1. Based on results of laboratory testing, it is possible to differentiate between fabric systems. In general, a fabric system with high mass and thickness tended to have low values of air permeability, evaporative heat loss and absorbency; and high resistance to water vapour diffusion and dry heat loss.

2. It is also possible to differentiate between garment systems based on physiological

and subjective comfort measures from human wear trials, but this ability to differentiate differed for various exercise levels.

3. Differences in physiological and subjective measures between garment systems are consistent with data from Part I of this study which indicate that generally fabric systems with high air permeability, evaporative heat loss, absorbency, and low resistance to water vapour diffusion and dry heat loss will cause less heat strain and be perceived as comfortable.

4. a) In this study, regression models indicate that different physical properties determine different physiological measures, and these differed for various exercise levels.
   b) In this study, regression models indicated that the same physical textile properties determine corresponding subjective comfort measures for both physical effort levels.
   c) Different textile properties may predict different physiological measures, it is essential when using a predictive comfort model that one clearly define the dependent variable of interest.
   d) Due to high correlation among both sets of independent and dependent variables, reliability of the regression models generated from this study is questionable. Therefore, precise conclusions cannot be made as to which textile properties will best predict given physiological and subjective measures.

5. The regression models in this study suggest that it would be necessary to measure only one or two textile properties in order to predict physiological and subjective comfort. This is due to the fact that physical properties measured were highly intercorrelated.

6. Coefficients of determination for physiological and subjective models were higher

for low than for strenuous activity levels. This is an indication that one is able to predict a higher percentage of variation in the dependent variable at low levels of physical activity. It may also be concluded that physiological and subjective comfort measures during heavy exercise are affected by other variables such as exercise level and environmental conditions in addition those included in the regression models.

Recommendations

The recommendations generated from this study are the following:

1. On all accounts, prototype garment systems outperformed the current in-service CB protective garment system. It is therefore recommended, based on the results from physiological and subjective human wear trials, that a CB protective garment system be adopted by the Canadian Forces that will allow for a high degree of air permeability, evaporative heat loss, absorbency, and low resistance to water vapour diffusion and dry heat loss.

2. Research of this kind should be carried out by establishing a wear trial protocol which would include all garment systems to be investigated, and both physiological and subjective comfort measures. This would allow for fabric sampling of garments worn in the wear trials, easier analysis of data, better comparison between a greater number of garment systems, and a combination of physiological and subjective data for the development and comparison of comfort models.

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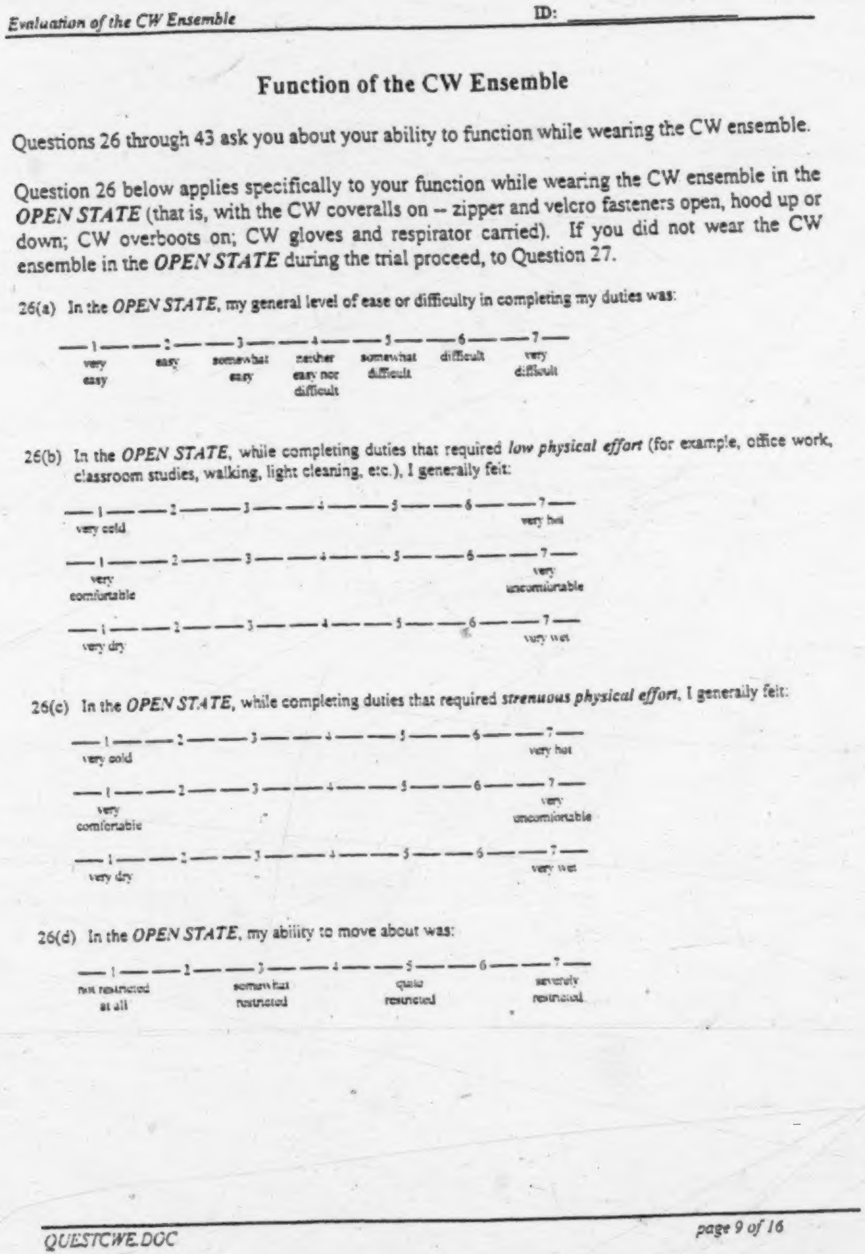
Appendix A



Evaluation of the CW Ensemble ID: ________________

Function of the CW Ensemble

Questions 26 through 43 ask you about your ability to function while wearing the CW ensemble.

Question 26 below applies specifically to your function while wearing the CW ensemble in the ***OPEN STATE*** (that is, with the CW coveralls on -- zipper and velcro fasteners open, hood up or down; CW overboots on; CW gloves and respirator carried). If you did not wear the CW ensemble in the ***OPEN STATE*** during the trial proceed, to Question 27.

26(a) In the ***OPEN STATE***, my general level of ease or difficulty in completing my duties was:

1	2	3	4	5	6	7
very easy	easy	somewhat easy	neither easy nor difficult	somewhat difficult	difficult	very difficult

26(b) In the ***OPEN STATE***, while completing duties that required ***low physical effort*** (for example, office work, classroom studies, walking, light cleaning, etc.), I generally felt:

1	2	3	4	5	6	7
very cold						very hot

1	2	3	4	5	6	7
very comfortable						very uncomfortable

1	2	3	4	5	6	7
very dry						very wet

26(c) In the ***OPEN STATE***, while completing duties that required ***strenuous physical effort***, I generally felt:

1	2	3	4	5	6	7
very cold						very hot

1	2	3	4	5	6	7
very comfortable						very uncomfortable

1	2	3	4	5	6	7
very dry						very wet

26(d) In the ***OPEN STATE***, my ability to move about was:

1	2	3	4	5	6	7
not restricted at all		somewhat restricted		quite restricted		severely restricted

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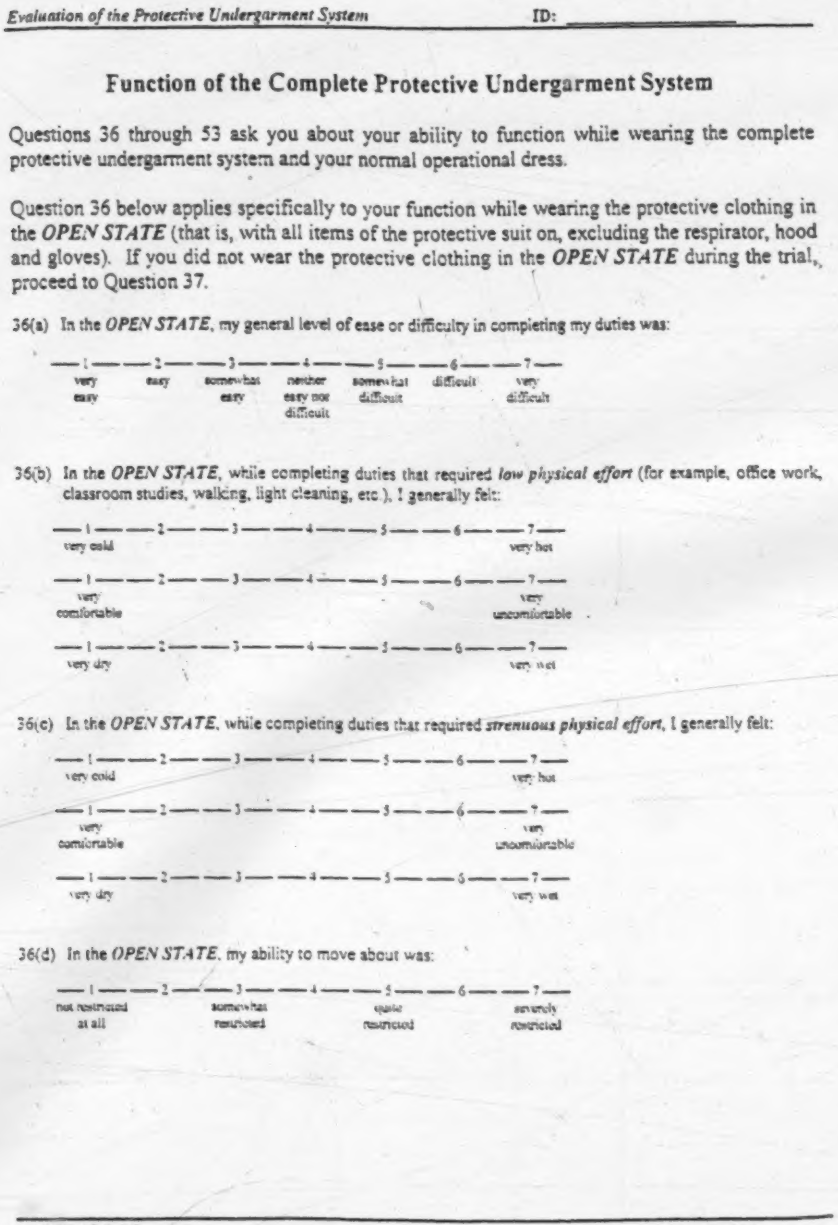
Appendix A1. Three comfort related questions for garment system 3 from a questionnaire used in the 1995 field trial to assess comfort and wear.



Evaluation of the Protective Undergarment System ID: ____________

Function of the Complete Protective Undergarment System

Questions 36 through 53 ask you about your ability to function while wearing the complete protective undergarment system and your normal operational dress.

Question 36 below applies specifically to your function while wearing the protective clothing in the ***OPEN STATE*** (that is, with all items of the protective suit on, excluding the respirator, hood and gloves). If you did not wear the protective clothing in the ***OPEN STATE*** during the trial, proceed to Question 37.

36(a) In the ***OPEN STATE***, my general level of ease or difficulty in completing my duties was:

1	2	3	4	5	6	7
very easy	easy	somewhat easy	neither easy nor difficult	somewhat difficult	difficult	very difficult

36(b) In the ***OPEN STATE***, while completing duties that required ***low physical effort*** (for example, office work, classroom studies, walking, light cleaning, etc.), I generally felt:

1	2	3	4	5	6	7
very cold						very hot

1	2	3	4	5	6	7
very comfortable						very uncomfortable

1	2	3	4	5	6	7
very dry						very wet

36(c) In the ***OPEN STATE***, while completing duties that required ***strenuous physical effort***, I generally felt:

1	2	3	4	5	6	7
very cold						very hot

1	2	3	4	5	6	7
very comfortable						very uncomfortable

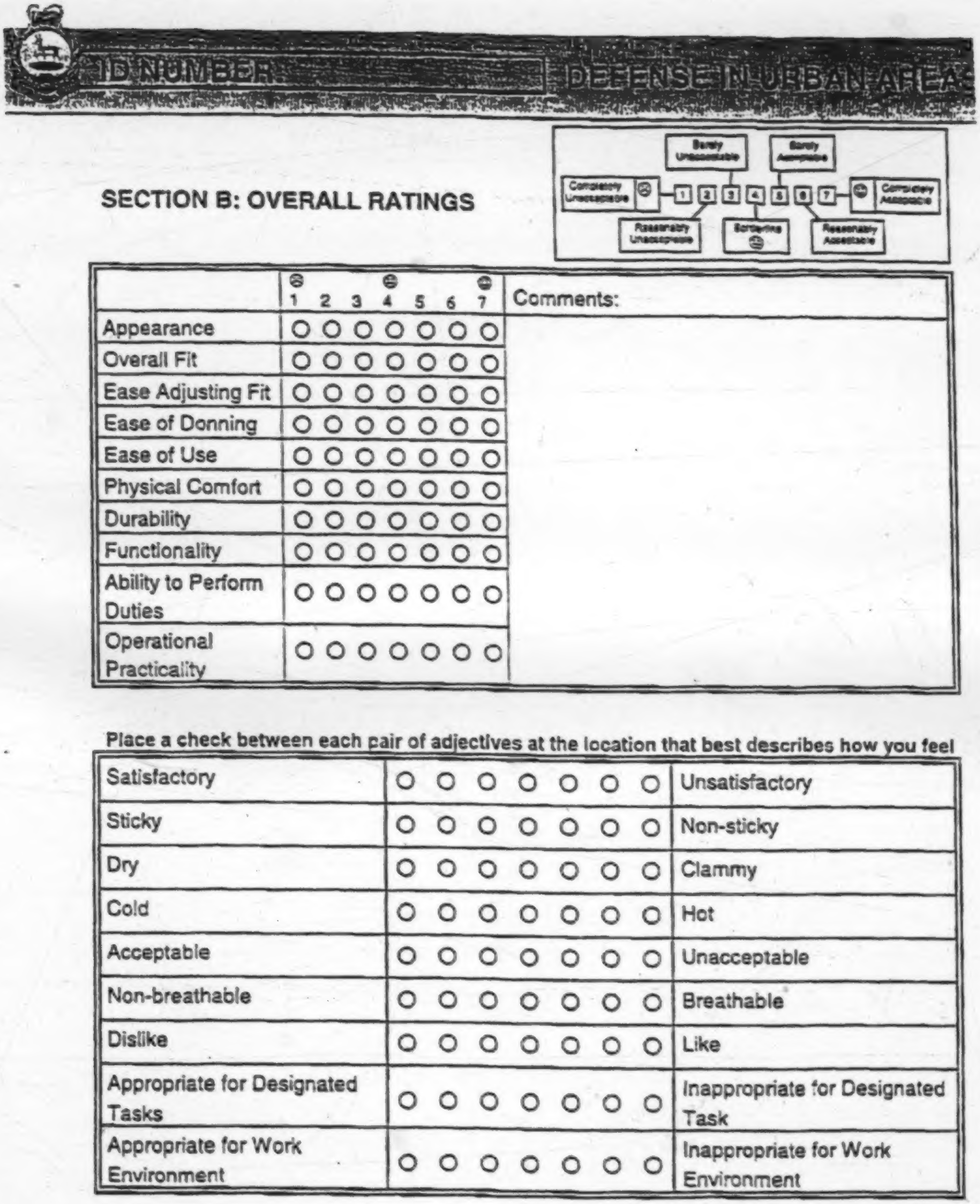
1	2	3	4	5	6	7
very dry						very wet

36(d) In the ***OPEN STATE***, my ability to move about was:

1	2	3	4	5	6	7
not restricted at all		somewhat restricted		quite restricted		severely restricted

QUESTUG.DOC *page 13 of 20*

Appendix A2. Three comfort related questions for garment system 4 from a questionnaire used in the 1995 field trial to assess comfort and wear.



ID NUMBER:

DEFENSE IN URBAN AREA

SECTION B: OVERALL RATINGS

Barely Unacceptable
Barely Acceptable
Completely Unacceptable ☹ 1 2 3 4 5 6 7 ☺ Completely Acceptable
Reasonably Unacceptable
Borderline 😐
Reasonably Acceptable

	☹ 1	2	3	😐 4	5	6	☺ 7	Comments:
Appearance	○	○	○	○	○	○	○	
Overall Fit	○	○	○	○	○	○	○	
Ease Adjusting Fit	○	○	○	○	○	○	○	
Ease of Donning	○	○	○	○	○	○	○	
Ease of Use	○	○	○	○	○	○	○	
Physical Comfort	○	○	○	○	○	○	○	
Durability	○	○	○	○	○	○	○	
Functionality	○	○	○	○	○	○	○	
Ability to Perform Duties	○	○	○	○	○	○	○	
Operational Practicality	○	○	○	○	○	○	○	

Place a check between each pair of adjectives at the location that best describes how you feel

Satisfactory	○	○	○	○	○	○	○	Unsatisfactory
Sticky	○	○	○	○	○	○	○	Non-sticky
Dry	○	○	○	○	○	○	○	Clammy
Cold	○	○	○	○	○	○	○	Hot
Acceptable	○	○	○	○	○	○	○	Unacceptable
Non-breathable	○	○	○	○	○	○	○	Breathable
Dislike	○	○	○	○	○	○	○	Like
Appropriate for Designated Tasks	○	○	○	○	○	○	○	Inappropriate for Designated Task
Appropriate for Work Environment	○	○	○	○	○	○	○	Inappropriate for Work Environment

Appendix A3. Comfort related questions for garment systems 1 and 2 taken from a questionnaire used in the 1998 Gagetown field trial to assess wear and comfort.

Appendix B

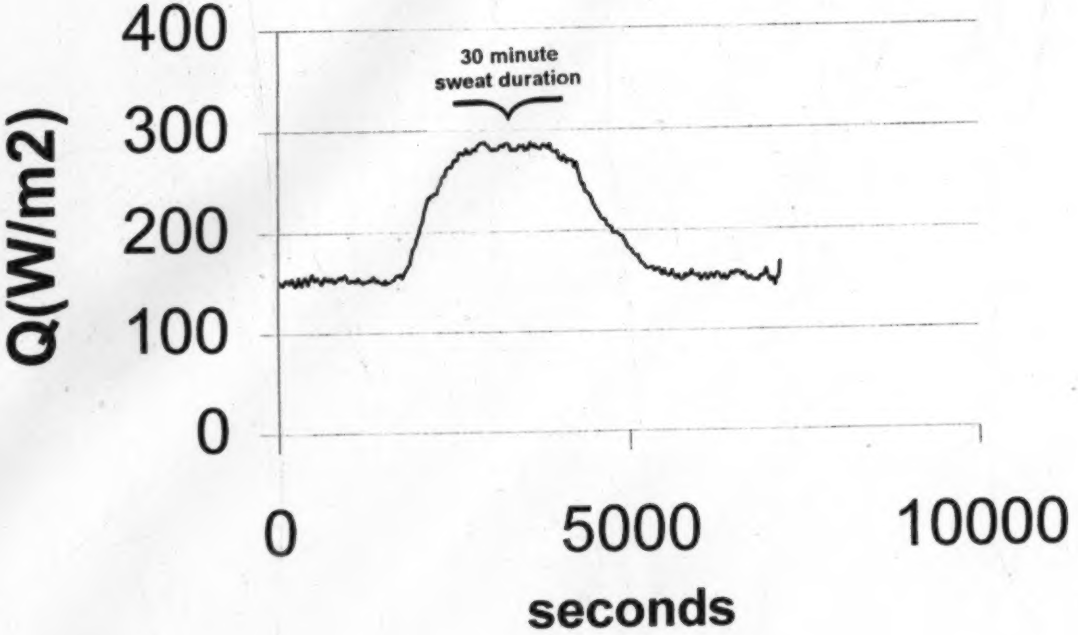


Plate temperature = 35°C
Chamber temperature = 20°C
Chamber relative humidity = 50%
Sweat rate = 360g/m^2/hr

Appendix B. A typical example of heat loss from a fabric system before, during and after a period of sweating.

Appendix C

Correlations for light intensity exercise

		1994 heart rate (rate of change)	1994 maximum heart rate	1994 heart rate - (maximum change)	1994 mean skin temperature (rate of change)	1994 mean skin temperature (maximum)	1994 mean skin temperature (maximum change)	1994 rectal temperature (rate of change)	1994 rectal temperature (maximum)	1994 rectal temperature (maximum change)	Tolerance time 1994
1994 heart rate (rate of change)	Pearson Correlation	1.000	.765**	.743**	.513	.426	.195	.550*	-.302	-.260	-.600*
	Sig. (2-tailed)	.	.001	.002	.061	.129	.505	.041	.293	.369	.023
	N	14	14	14	14	14	14	14	14	14	14
1994 maximum heart rate	Pearson Correlation	.765**	1.000	.925**	.420	.059	.299	.066	-.228	-.392	-.217
	Sig. (2-tailed)	.001	.	.000	.135	.842	.299	.822	.432	.166	.457
	N	14	14	14	14	14	14	14	14	14	14
1994 heart rate - (maximum change)	Pearson Correlation	.743**	.925**	1.000	.190	.056	.185	.098	-.094	-.108	-.108
	Sig. (2-tailed)	.002	.000	.	.515	.849	.527	.740	.749	.714	.714
	N	14	14	14	14	14	14	14	14	14	14
1994 mean skin temperature (rate of change)	Pearson Correlation	.513	.420	.190	1.000	.311	.542*	.548*	-.410	-.682**	-.569*
	Sig. (2-tailed)	.061	.135	.515	.	.280	.045	.042	.146	.007	.034
	N	14	14	14	14	14	14	14	14	14	14
1994 mean skin temperature (maximum)	Pearson Correlation	.426	.059	.056	.311	1.000	.523	.453	.143	.195	-.339
	Sig. (2-tailed)	.129	.842	.849	.280	.	.055	.104	.625	.503	.236
	N	14	14	14	14	14	14	14	14	14	14
1994 mean skin temperature (maximum change)	Pearson Correlation	.195	.299	.185	.542*	.523	1.000	-.006	.158	-.221	.152
	Sig. (2-tailed)	.505	.299	.527	.045	.055	.	.983	.590	.447	.605
	N	14	14	14	14	14	14	14	14	14	14
1994 rectal temperature (rate of change)	Pearson Correlation	.550*	.066	.098	.548*	.453	-.006	1.000	-.070	.043	-.775**
	Sig. (2-tailed)	.041	.822	.740	.042	.104	.983	.	.812	.884	.001
	N	14	14	14	14	14	14	14	14	14	14
1994 rectal temperature (maximum)	Pearson Correlation	-.302	-.228	-.094	-.410	.143	.158	-.070	1.000	.790**	.435
	Sig. (2-tailed)	.293	.432	.749	.146	.625	.590	.812	.	.001	.120
	N	14	14	14	14	14	14	14	14	14	14
1994 rectal temperature (maximum change)	Pearson Correlation	-.260	-.392	-.108	-.682**	.195	-.221	.043	.790**	1.000	.277
	Sig. (2-tailed)	.369	.166	.714	.007	.503	.447	.884	.001	.	.338
	N	14	14	14	14	14	14	14	14	14	14
Tolerance time 1994	Pearson Correlation	-.600*	-.217	-.108	-.569*	-.339	.152	-.775**	.435	.277	1.000
	Sig. (2-tailed)	.023	.457	.714	.034	.236	.605	.001	.120	.338	.
	N	14	14	14	14	14	14	14	14	14	14

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix C1: Correlations between physiological measures for light intensity exercise.

Correlations for moderate intensity exercise

		1994 heart rate (rate of change)	1994 maximum heart rate	1994 heart rate - (maximum change)	1994 mean skin temperature (rate of change)	1994 mean skin temperature (maximum)	1994 mean skin temperature (maximum change)	1994 rectal temperature (rate of change)	1994 rectal temperature (maximum)	1994 rectal temperature (maximum change)	Tolerance time 1994
1994 heart rate (rate of change)	Pearson Correlation	1.000	.395	.521*	.242	.140	-.269	.758**	-.235	.053	-.595*
	Sig. (2-tailed)	.	.130	.038	.366	.604	.314	.001	.380	.846	.015
	N	16	16	16	16	16	16	16	16	16	16
1994 maximum heart rate	Pearson Correlation	.395	1.000	.848**	-.198	.539*	.103	.365	.597*	.607*	.287
	Sig. (2-tailed)	.130	.	.000	.463	.031	.704	.165	.015	.013	.281
	N	16	16	16	16	16	16	16	16	16	16
1994 heart rate - (maximum change)	Pearson Correlation	.521*	.848**	1.000	-.440	.375	-.132	.374	.433	.680**	.346
	Sig. (2-tailed)	.038	.000	.	.088	.153	.625	.153	.094	.004	.189
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (rate of change)	Pearson Correlation	.242	-.198	-.440	1.000	.305	.560*	.414	-.384	-.407	-.749**
	Sig. (2-tailed)	.366	.463	.088	.	.251	.024	.111	.142	.118	.001
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (maximum)	Pearson Correlation	.140	.539*	.375	.305	1.000	.680**	.460	.489	.510*	.088
	Sig. (2-tailed)	.604	.031	.153	.251	.	.004	.073	.054	.043	.745
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (maximum change)	Pearson Correlation	-.269	.103	-.132	.560*	.680**	1.000	.090	.130	.168	.078
	Sig. (2-tailed)	.314	.704	.625	.024	.004	.	.739	.632	.534	.774
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (rate of change)	Pearson Correlation	.758**	.365	.374	.414	.460	.090	1.000	.034	.404	-.520*
	Sig. (2-tailed)	.001	.165	.153	.111	.073	.739	.	.902	.121	.039
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (maximum)	Pearson Correlation	-.235	.597*	.433	-.384	.489	.130	.034	1.000	.676**	.611*
	Sig. (2-tailed)	.380	.015	.094	.142	.054	.632	.902	.	.004	.012
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (maximum change)	Pearson Correlation	.053	.607*	.680**	-.407	.510*	.168	.404	.676**	1.000	.563*
	Sig. (2-tailed)	.846	.013	.004	.118	.043	.534	.121	.004	.	.023
	N	16	16	16	16	16	16	16	16	16	16
Tolerance time 1994	Pearson Correlation	-.595*	.287	.346	-.749**	.088	.078	-.520*	.611*	.563*	1.000
	Sig. (2-tailed)	.015	.281	.189	.001	.745	.774	.039	.012	.023	.
	N	16	16	16	16	16	16	16	16	16	16

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix C2: Correlations between physiological measures for Moderate intensity exercise.

Correlations for heavy intensity exercise

		1994 heart rate (rate of change)	1994 maximum heart rate	1994 heart rate - (maximum change)	1994 mean skin temperature (rate of change)	1994 mean skin temperature (maximum)	1994 mean skin temperature (maximum change)	1994 rectal temperature (rate of change)	1994 rectal temperature (maximum)	1994 rectal temperature (maximum change)	Tolerance time 1994
1994 heart rate (rate of change)	Pearson Correlation	1.000	.628**	.443	.665**	-.220	-.241	.452	-.205	-.343	-.839**
	Sig. (2-tailed)	.	.009	.086	.005	.412	.368	.079	.446	.193	.000
	N	16	16	16	16	16	16	16	16	16	16
1994 maximum heart rate	Pearson Correlation	.628**	1.000	.641**	.378	-.228	-.017	-.043	-.230	-.381	-.379
	Sig. (2-tailed)	.009	.	.007	.148	.395	.951	.873	.391	.145	.148
	N	16	16	16	16	16	16	16	16	16	16
1994 heart rate - (maximum change)	Pearson Correlation	.443	.641**	1.000	-.055	-.231	-.065	-.059	-.278	-.032	.026
	Sig. (2-tailed)	.086	.007	.	.841	.390	.812	.829	.298	.907	.925
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (rate of change)	Pearson Correlation	.665**	.378	-.055	1.000	.429	.350	.516*	.065	-.265	-.801**
	Sig. (2-tailed)	.005	.148	.841	.	.097	.184	.041	.811	.321	.000
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (maximum)	Pearson Correlation	-.220	-.228	-.231	.429	1.000	.845**	.160	.339	.193	.046
	Sig. (2-tailed)	.412	.395	.390	.097	.	.000	.554	.200	.473	.867
	N	16	16	16	16	16	16	16	16	16	16
1994 mean skin temperature (maximum change)	Pearson Correlation	-.241	-.017	-.065	.350	.845**	1.000	.183	.510*	.364	.218
	Sig. (2-tailed)	.368	.951	.812	.184	.000	.	.498	.044	.166	.416
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (rate of change)	Pearson Correlation	.452	-.043	-.059	.516*	.160	.183	1.000	.615*	.556*	-.417
	Sig. (2-tailed)	.079	.873	.829	.041	.554	.498	.	.011	.025	.108
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (maximum)	Pearson Correlation	-.205	-.230	-.278	.065	.339	.510*	.615*	1.000	.803**	.234
	Sig. (2-tailed)	.446	.391	.298	.811	.200	.044	.011	.	.000	.384
	N	16	16	16	16	16	16	16	16	16	16
1994 rectal temperature (maximum change)	Pearson Correlation	-.343	-.381	-.032	-.265	.193	.364	.556*	.803**	1.000	.487
	Sig. (2-tailed)	.193	.145	.907	.321	.473	.166	.025	.000	.	.056
	N	16	16	16	16	16	16	16	16	16	16
Tolerance time 1994	Pearson Correlation	-.839**	-.379	.026	-.801**	.046	.218	-.417	.234	.487	1.000
	Sig. (2-tailed)	.000	.148	.925	.000	.867	.416	.108	.384	.056	.
	N	16	16	16	16	16	16	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix C3: Correlations between physiological measures for heavy intensity exercise.

Appendix D

Correlations for garment systems 2 and 3

		1997 heart rate (rate of change)	1997 heart rate (maximum)	1997 heart rate (maximum change)	1997 mean skin temperature (rate of change)	1997 mean skin temperature (maximum)	1997 mean skin temperature (maximum change)	1997 rectal temperature (rate of change)	1997 rectal temperature (maximum)	1997 rectal temperature (maximum change)	tolerance time 1997
1997 heart rate (rate of change)	Pearson Correlation	1.000	.633**	.338	.461	.328	-.040	.713**	-.244	-.351	-.825**
	Sig. (2-tailed)	.	.009	.200	.072	.215	.884	.002	.363	.182	.000
	N	16	16	16	16	16	16	16	16	16	16
1997 heart rate (maximum)	Pearson Correlation	.633**	1.000	.411	.540*	.101	.167	.471	-.050	-.310	-.600*
	Sig. (2-tailed)	.009	.	.113	.031	.709	.537	.065	.853	.242	.014
	N	16	16	16	16	16	16	16	16	16	16
1997 heart rate (maximum change)	Pearson Correlation	.338	.411	1.000	-.218	-.095	-.147	-.120	-.256	.005	.083
	Sig. (2-tailed)	.200	.113	.	.417	.728	.588	.657	.338	.985	.759
	N	16	16	16	16	16	16	16	16	16	16
1997 mean skin temperature (rate of change)	Pearson Correlation	.461	.540*	-.218	1.000	.125	.441	.527*	.147	-.441	-.635**
	Sig. (2-tailed)	.072	.031	.417	.	.645	.087	.036	.587	.087	.008
	N	16	16	16	16	16	16	16	16	16	16
1997 mean skin temperature (maximum)	Pearson Correlation	.328	.101	-.095	.125	1.000	.247	.663**	.540*	.556*	-.486
	Sig. (2-tailed)	.215	.709	.728	.645	.	.356	.005	.031	.025	.056
	N	16	16	16	16	16	16	16	16	16	16
1997 mean skin temperature (maximum change)	Pearson Correlation	-.040	.167	-.147	.441	.247	1.000	.034	.343	.111	.000
	Sig. (2-tailed)	.884	.537	.588	.087	.356	.	.902	.193	.683	1.000
	N	16	16	16	16	16	16	16	16	16	16
1997 rectal temperature (rate of change)	Pearson Correlation	.713**	.471	-.120	.527*	.663**	.034	1.000	.215	.093	-.918**
	Sig. (2-tailed)	.002	.065	.657	.036	.005	.902	.	.424	.732	.000
	N	16	16	16	16	16	16	16	16	16	16
1997 rectal temperature (maximum)	Pearson Correlation	-.244	-.050	-.256	.147	.540*	.343	.215	1.000	.691**	-.065
	Sig. (2-tailed)	.363	.853	.338	.587	.031	.193	.424	.	.003	.812
	N	16	16	16	16	16	16	16	16	16	16
1997 rectal temperature (maximum change)	Pearson Correlation	-.351	-.310	.005	-.441	.556*	.111	.093	.691**	1.000	.211
	Sig. (2-tailed)	.182	.242	.985	.087	.025	.683	.732	.003	.	.433
	N	16	16	16	16	16	16	16	16	16	16
tolerance time 1997	Pearson Correlation	-.825**	-.600*	.083	-.635**	-.486	.000	-.918**	-.065	.211	1.000
	Sig. (2-tailed)	.000	.014	.759	.008	.056	1.000	.000	.812	.433	.
	N	16	16	16	16	16	16	16	16	16	16

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Appendix D. Correlations between physiological measures for garment systems 2 and 3.

Appendix E

Correlations (low effort)

		very cold vs. very hot	very comfortable vs very uncomfortable	very dry vs. very wet	total comfort rating
very cold vs. very hot	Pearson Correlation	1.000	.493*	.035	.565**
	Sig. (2-tailed)	.	.027	.884	.009
	N	20	20	20	20
very comfortable vs very uncomfortable	Pearson Correlation	.493*	1.000	.640**	.924**
	Sig. (2-tailed)	.027	.	.002	.000
	N	20	20	20	20
very dry vs. very wet	Pearson Correlation	.035	.640**	1.000	.803**
	Sig. (2-tailed)	.884	.002	.	.000
	N	20	20	20	20
total comfort rating	Pearson Correlation	.565**	.924**	.803**	1.000
	Sig. (2-tailed)	.009	.000	.000	.
	N	20	20	20	20

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Correlations (strenuous effort)

		very cold vs. very hot	very comfortable vs very uncomfortable	very dry vs. very wet	total comfort rating
very cold vs. very hot	Pearson Correlation	1.000	.553*	.360	.725**
	Sig. (2-tailed)	.	.017	.142	.001
	N	18	18	18	18
very comfortable vs very uncomfortable	Pearson Correlation	.553*	1.000	.767**	.930**
	Sig. (2-tailed)	.017	.	.000	.000
	N	18	18	18	18
very dry vs. very wet	Pearson Correlation	.360	.767**	1.000	.865**
	Sig. (2-tailed)	.142	.000	.	.000
	N	18	18	18	18
total comfort rating	Pearson Correlation	.725**	.930**	.865**	1.000
	Sig. (2-tailed)	.001	.000	.000	.
	N	18	18	18	18

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix E. Correlations between subjective comfort measures at low and strenuous physical effort levels.

Appendix F

Regression for mean skin temperature (rate of change) moderate intensity

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Sweating Guarded Hot Plate (W/m2)	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: 1994 mean skin temperature (rate of change)

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.527[a]	.277	.226	.44912E-02

a. Predictors: (Constant), Sweating Guarded Hot Plate (W/m2)

b. Dependent Variable: 1994 mean skin temperature (rate of change)

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1.128E-03	1	1.128E-03	5.371	.036[a]
	Residual	2.940E-03	14	2.100E-04		
	Total	4.068E-03	15			

a. Predictors: (Constant), Sweating Guarded Hot Plate (W/m2)

b. Dependent Variable: 1994 mean skin temperature (rate of change)

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.119	.023		5.218	.000
	Sweating Guarded Hot Plate (W/m2)	-1.896E-04	.000	-.527	-2.317	.036

a. Dependent Variable: 1994 mean skin temperature (rate of change)

Appendix F: Typical multiple regression output with plots for mean skin temperature (rate of change) moderate intensity exercise.

Excluded Variables[b]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics
						Tolerance
1	air permeability (cm3/cm2.s-1)	.617[a]	.888	.391	.239	.109
	Method 49 (mm still air)	.001[a]	.002	.999	.001	.185
	absorbency (g/sec)	.010[a]	.016	.987	.005	.150
	VBW (mm still air)	-.317[a]	-1.024	.325	-.273	.537
	thermal resistance (m2K/W)	.188[a]	.230	.821	.064	8.352E-02

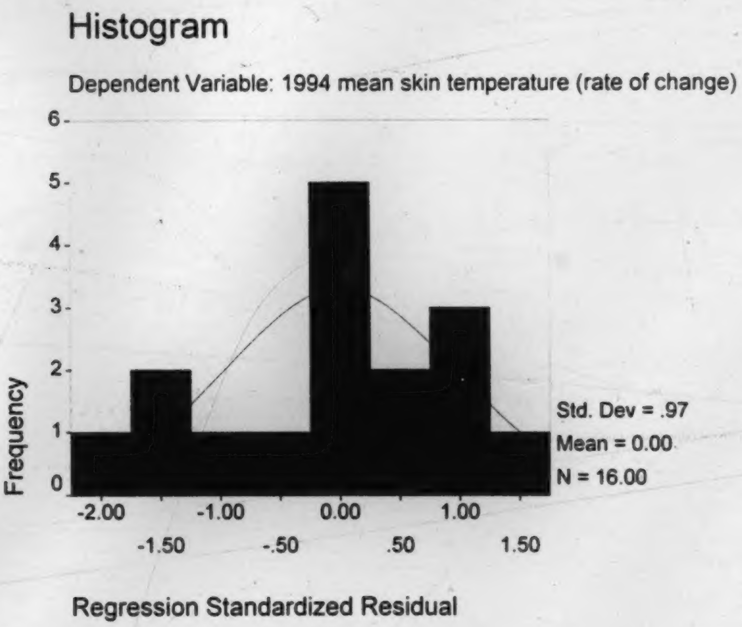
a. Predictors in the Model: (Constant), Sweating Guarded Hot Plate (W/m2)

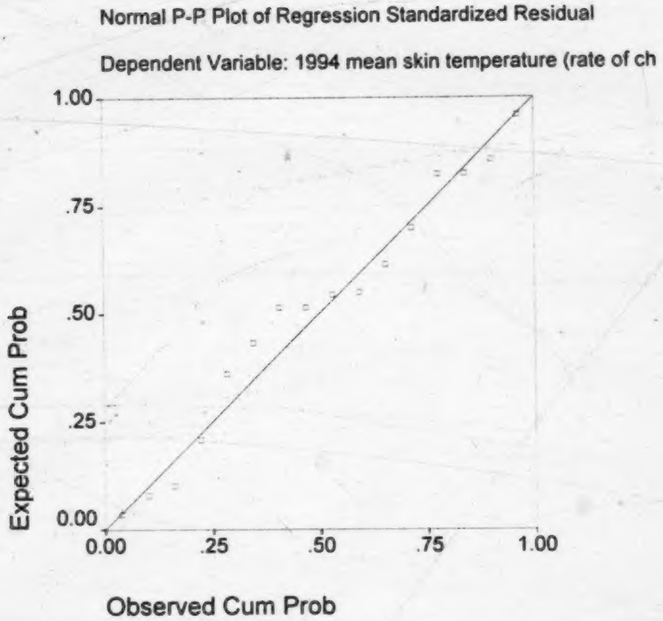
b. Dependent Variable: 1994 mean skin temperature (rate of change)

Residuals Statistics[a]

	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	5.547E-02	7.639E-02	6.663E-02	.67109E-03	16
Residual	-2.62E-02	2.527E-02	-3.04E-18	.39998E-02	16
Std. Predicted Value	-1.287	1.126	.000	1.000	16
Std. Residual	-1.806	1.744	.000	.966	16

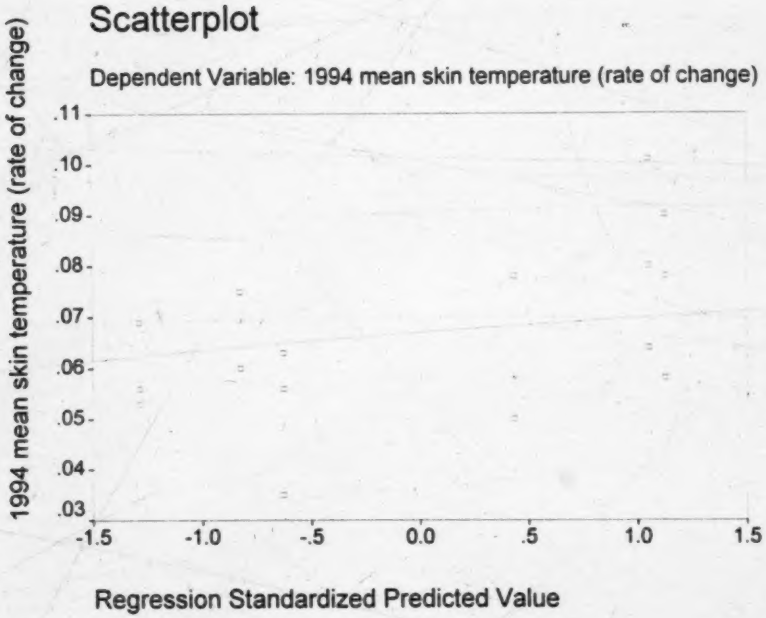
a. Dependent Variable: 1994 mean skin temperature (rate of change)





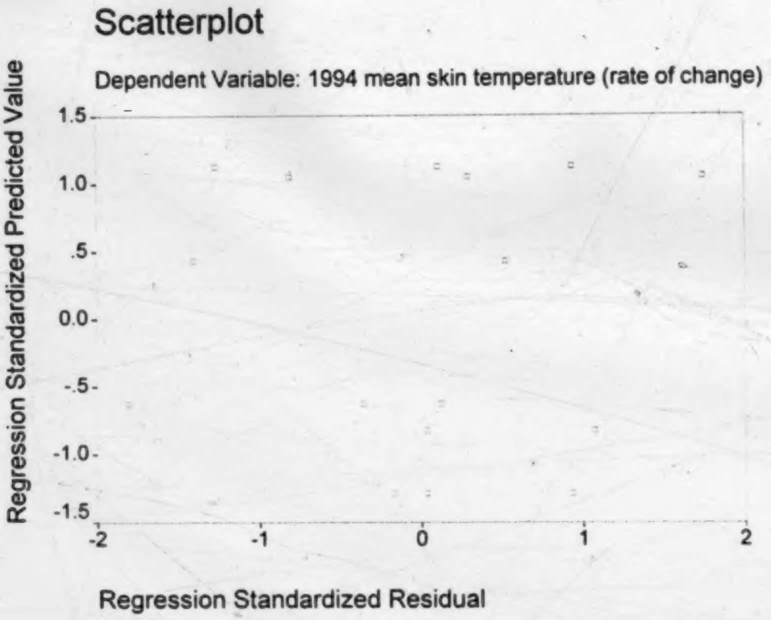
Normal P-P Plot of Regression Standardized Residual

Dependent Variable: 1994 mean skin temperature (rate of ch



Scatterplot

Dependent Variable: 1994 mean skin temperature (rate of change)


Scatterplot
Dependent Variable: 1994 mean skin temperature (rate of change)
Regression Standardized Predicted Value
1.5
1.0
.5
0.0
-.5
-1.0
-1.5
-2
-1
0
1
2
Regression Standardized Residual

Appendix G

Regression for "comfortable" (low effort)

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	air permeability (cm3/cm2.s-1)	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: very comfortable vs very uncomfortable

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.692[a]	.479	.450	.72

a. Predictors: (Constant), air permeability (cm3/cm2.s-1)

b. Dependent Variable: very comfortable vs very uncomfortable

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	8.618	1	8.618	16.535	.001[a]
	Residual	9.382	18	.521		
	Total	18.000	19			

a. Predictors: (Constant), air permeability (cm3/cm2.s-1)

b. Dependent Variable: very comfortable vs very uncomfortable

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	7.138	.788		9.053	.000		
	air permeability (cm3/cm2.s-1)	-7.992E-02	.020	-.692	-4.066	.001	1.000	1.000

a. Dependent Variable: very comfortable vs very uncomfortable

Appendix G: Typical multiple regression output with plots for "very comfortable vs. very uncomfortable" for low physical effort.

Excluded Variables[b]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics		
						Tolerance	VIF	Minimum Tolerance
1	Method 49 (mm still air)	-.140	-.384	.706	-.093	.228	4.380	.228
	absorbency (g/sec)	.240	.514	.614	.124	.139	7.200	.139
	VBW (mm still air)	-.124	-.586	.566	-.141	.672	1.487	.672
	Sweating Guarded Hot Plate (W/m2)	-.114	-.307	.763	-.074	.220	4.540	.220
	thermal resistance (m2K/W)	-.015	-.033	.974	-.008	.137	7.326	.137

a. Predictors in the Model: (Constant), air permeability (cm3/cm2.s-1)

b. Dependent Variable: very comfortable vs very uncomfortable

Collinearity Diagnostics[a]

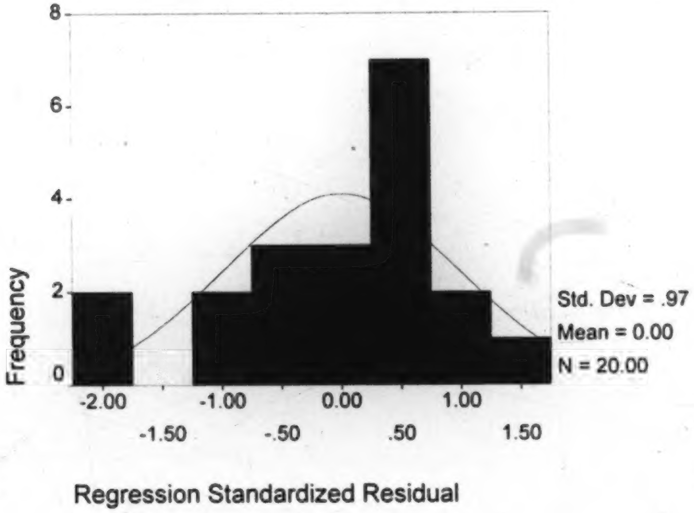
Model	Dimension	Eigenvalue	Condition Index	Variance Proportions	
				(Constant)	air permeability (cm3/cm2.s-1)
1	1	1.979	1.000	.01	.01
	2	2.118E-02	9.665	.99	.99

a. Dependent Variable: very comfortable vs very uncomfortable

Residuals Statistics[a]

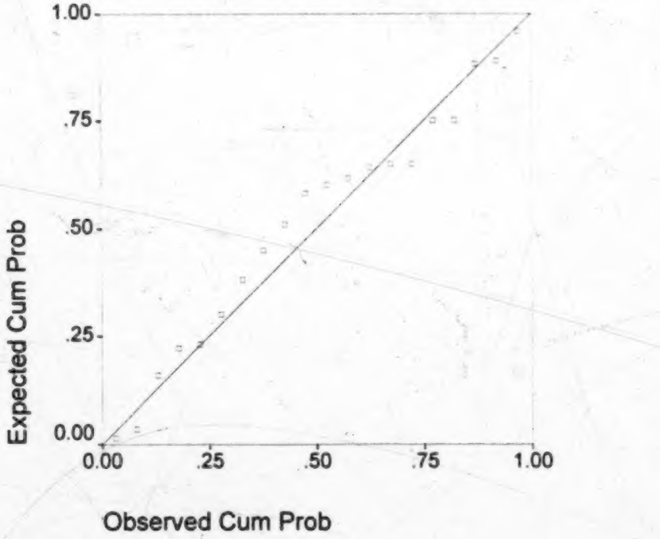
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.98	4.85	4.00	.67	20
Residual	-1.57	1.26	2.44E-16	.70	20
Std. Predicted Value	-1.513	1.263	.000	1.000	20
Std. Residual	-2.176	1.742	.000	.973	20

a. Dependent Variable: very comfortable vs very uncomfortable



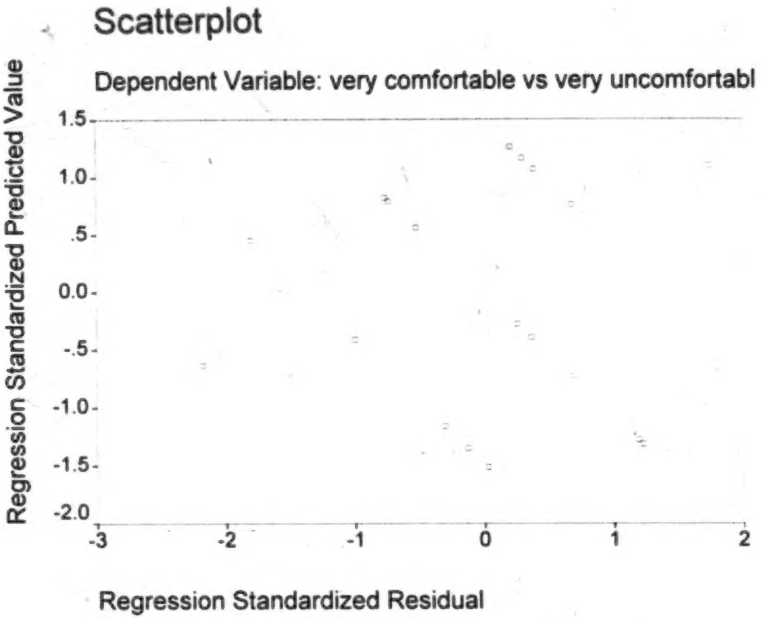
Histogram

Dependent Variable: very comfortable vs very uncomfortable



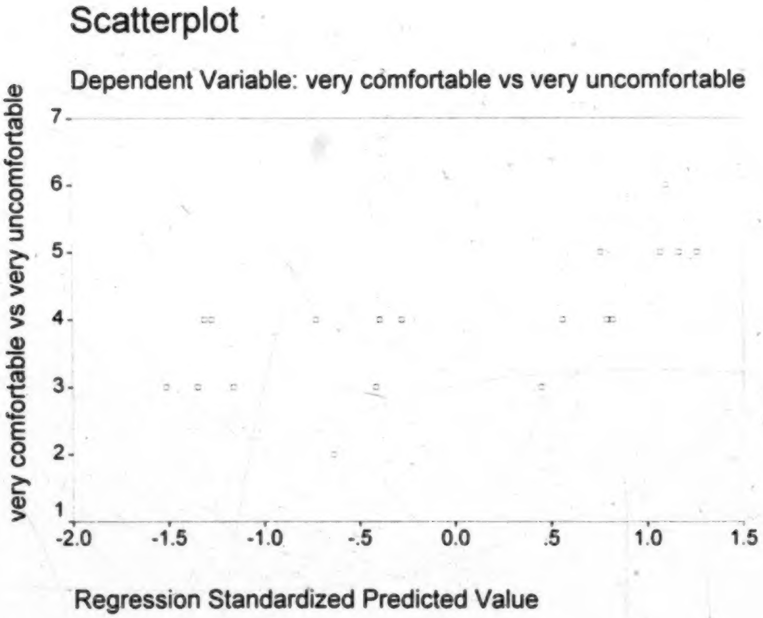
Normal P-P Plot of Regression Standardized Residual

Dependent Variable: very comfortable vs very uncomfortable



Scatterplot

Dependent Variable: very comfortable vs very uncomfortabl



Scatterplot

Dependent Variable: very comfortable vs very uncomfortable